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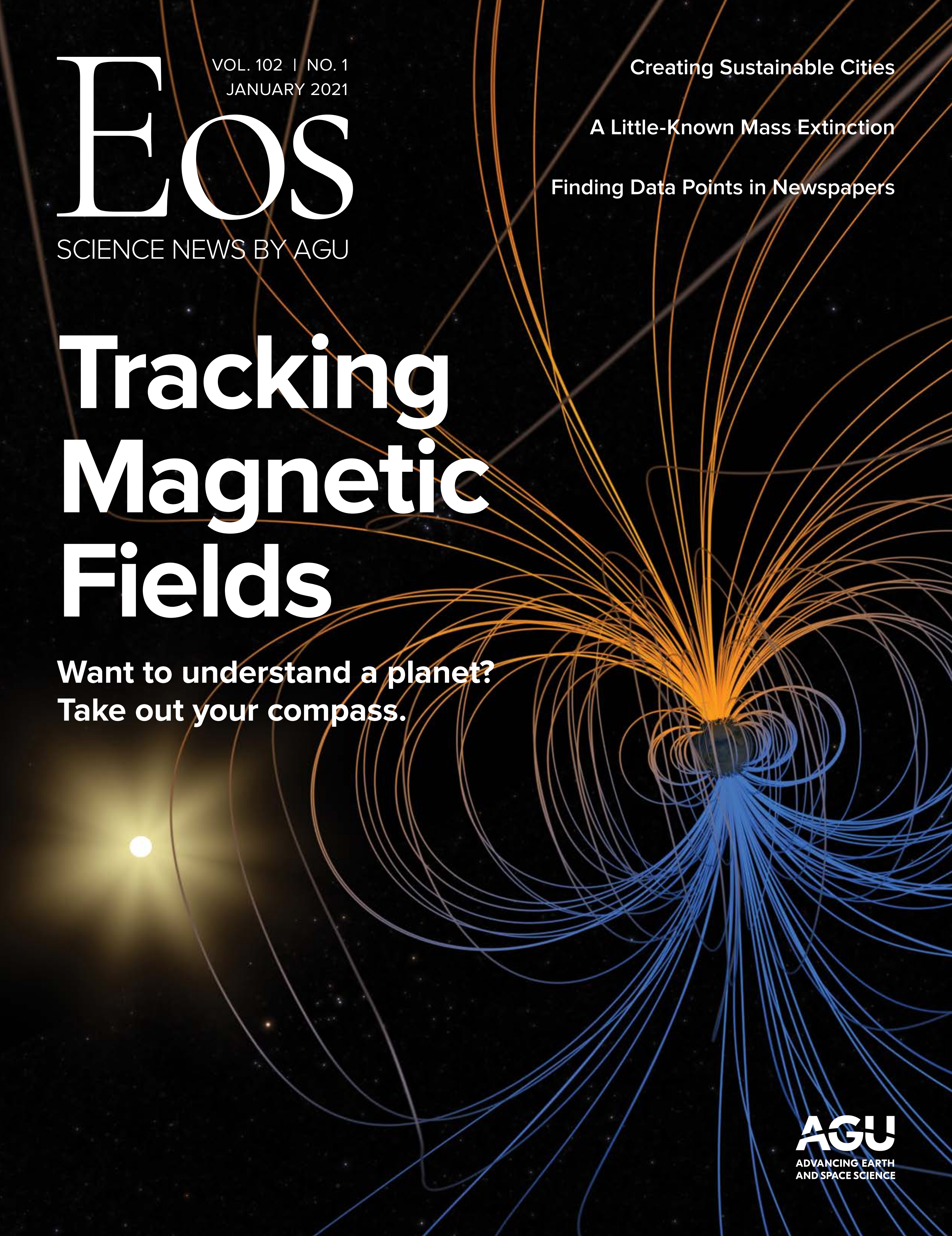
Eos

SCIENCE NEWS BY AGU

Creating Sustainable Cities

A Little-Known Mass Extinction

Finding Data Points in Newspapers



Tracking Magnetic Fields

Want to understand a planet? Take out your compass.

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FROM THE EDITOR

The Wobbly Anomaly and Other Magnetic Weirdness

"I always find it fascinating that something happening in such a remote, faraway place—Earth's core—can have a profound impact on our lives way out on the surface," said Julie Bowles as she helped us develop this issue. Bowles is an associate professor at the University of Wisconsin-Milwaukee and *Eos*'s science adviser for AGU's Geomagnetism, Paleomagnetism, and Electromagnetism section.

We dug into that impact Earth's magnetic field has on all of us for our January issue of *Eos*. A big reason we thought the topic was worth an entire issue is, as Bowles said, "there is a lot of interesting crossover between the magnetism community and many other Earth science communities." Indeed, this topic was originally suggested by Carol Stein, at the Department of Earth and Environmental Sciences at the University of Illinois at Chicago, *Eos*'s science adviser for AGU's Tectonophysics section, who noted the importance of understanding magnetism for so many scientists throughout AGU's sections.

You can flip through these pages to see that convergence. Manasvi Lingam starts us off on page 24 with an appropriately poetic introduction for a discussion about a force we cannot see generated by a core we cannot reach and how that has created unique conditions for the only place in the universe where we know life exists. "Resolving the riddle" of these relationships, writes Lingam, requires knowledge from geology, astronomy, plasma physics, microbiology, evolutionary biology, and myriad other disciplines.

The ideas raised here lead us into another fascinating discussion about "how pervasive magmatism is throughout the solar system," said Stein. So on page 36, we offer you "A Field Guide to the Magnetic Solar System." This tourist excursion leads you from Mercury out to the ice giants and explains what your magnetic compass will show you at each destination and what that means about the planet beneath your feet. We hope you enjoy this interplanetary adventure.

Finally, we couldn't cover studies of the magnetic field without recognizing how *truly strange it is*. In "The Herky-Jerky Weirdness of Earth's Magnetic Field" (p. 30), we take a look at the big dent known as the South Atlantic Anomaly, the origin of so-called geomagnetic jerks, and other oddities, "some of which have important societal implications," according to Bowles.

Unlike our pal Dr. Conrad Zimsky—did you really think I'd get all the way through this without a reference to *The Core*?—we know our understanding of geomagnetism is a lot better than "a best guess." We eagerly look forward to seeing more in this rapidly advancing science and covering it here in the pages of *Eos*.

Heather Goss, Editor in Chief

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Randy Fiser, Executive Director/CEO

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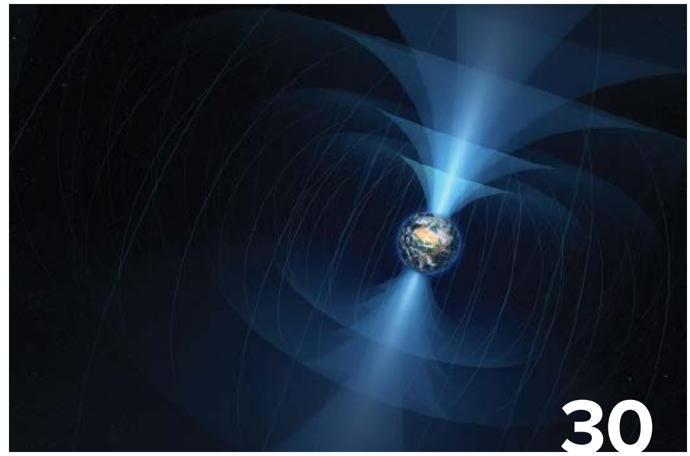

Features

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Columns

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Newspaper Archives Uncover Flood Risk

When figuring out flood risk, it's important to collect data on past flooding events. In some areas, detailed records of rainfall and stream gauges are available. But in regions that are dry or sparsely monitored, this critical information is missing.

Enter a different kind of record: newspapers. Areas that have experienced flooding likely had an accompanying local news story documenting the event, including what particular areas were flooded and the extent of damage.

Researchers have now used these newspaper records to act as a validation for flood risk maps. When they compared their flood maps to almost 20 years of newspaper articles, they found a high correlation between reported floods and predicted high-risk areas.

The scientists noted that their methods could be used by other researchers working in areas with spotty flood data. Their work may also be useful to policymakers and disaster managers to better prepare for future flooding.

Use What You Have

In the arid United Arab Emirates (UAE), flooding might not spring to mind as a regular event. But flash floods do occur in the UAE and are made worse by the proximity of cities to mountain foothills and the extent of urban impermeable surfaces, such as pavement.

Using geographic information systems (GIS), scientists can map out areas that may be prone to flooding using familiar criteria like slope, geology, rainfall, geomorphology, and land use. But these maps parse out only the potential risk. A historical measurement of floods—including locations, magnitudes, and frequencies—is an effective field check of predictions.

"The proverb says, 'Necessity is the mother of invention,'" said Mohamed Yagoub, professor of remote sensing and GIS at UAE University and lead author of the study, which appeared in *Natural Hazards* (bit.ly/GIS-modeling). "Researchers are sometimes faced with nonavailability and nonaccessibility of data. Therefore, they have to go around and use proxy means."

Mining the Archives

Using GIS, Yagoub and his team generated a traditional flood risk map for the area surrounding Fujairah, capital of the Fujairah emirate in the UAE. About 85% of the land area was in medium and low flood risk zones, mostly in mountainous terrain. The remaining 15% of land was urban areas and coastal plains, considered high to very high flood risk zones.

The United Arab Emirates, including Dubai, above, is prone to flash floods. Local newspapers are excellent proxies for flood risk maps, new research shows. Credit: iStock.com/Viktoriya Fivko

Yagoub explained that his team wanted to make sure these high-risk areas had flooded in the past. To check their model, the researchers turned to newspapers.

The researchers used five local papers (both Arabic- and English-language publications) to find records of historical flood events. "Reading many newspaper reports and scanning them for flood impact is a challenge," said Yagoub. "To automate this process, a Java program was developed to read the document file and extract important flood damage information using text-processing functions."

They compared their flood maps to almost 20 years of newspaper articles.

Using such a text-mining program, the team searched for words such as Fujairah, flood, evacuate, and water. From there, they gathered information on individual flooding events, including the general location, date, and what sort of damages occurred.

The team overlaid the historical events documented in newspaper articles on the map of potential flood zones to compare. They found that 84% of the reported floods were in high to very high flood risk zones.

"When it comes to flood risk, what we know is our probabilities calculations extrapolated over a map—that doesn't mean that they reflect the real situation," said Åse Johannessen, a water governance researcher at Lund University in Sweden who was not involved in the study.

Johannessen said that newspaper stories record real, not modeled, events, so they can be a good validation tool for risk mapping. "Not only that, it's also information about the actual damage and in all kinds of detail," she said.

Future Flood Prediction

Yagoub called newspapers a "forgotten treasure" in defining areas of flood risk. "I came to know that newspaper archives contain a wealth of information, and many research questions could be formulated based on this information," he said, adding that it would be even better if newspapers included accurate geographic coordinates of flooding events.

Johannessen also thinks newspapers provide a wealth of information, including how people behave in a flood. "For example, if you have a flood in a poor community, many people actually stay put because they want to save their assets." Knowing community behaviors can help emergency managers better prepare for extreme events.

She noted that newspapers also highlight the vulnerabilities in a system: transport disruption, accidents, and weaknesses of infrastructure. "[Those vulnerabilities are] not captured by a flood risk map."

"People talk about a cocktail of risks—that you don't really know which risks influence each other and have a cumulative cocktail of effects," Johannessen explained, adding that newspapers can help fill in the details of what happened during historical floods.

The goal of the study was "prevention, prevention, prevention," said Yagoub. "This type of flood-prone area map in digital form may be used as a database that could be shared among various government and nongovernment agencies concerned about floods."

"If planners can really understand the dynamics of a city and how to plan and where to put measures in a much more specific way, I think [this type of work] can be a big contribution," said Johannessen.

By **Sarah Derouin** (@Sarah_Derouin), Science Writer

Powerful Glacial Floods Heave Himalayan Boulders

Enormous boulders in Himalayan riverbeds, like this one in the Sunkoshi River channel, were likely transported by glacial lake outburst floods. Credit: Maarten Lupker

Enormous boulders—10 meters or more in diameter—litter many river channels in the Himalayas. Scientists have now age dated several of these behemoths and estimated the flow velocities necessary to have heaved them.

The boulders were likely set in motion thousands of years ago by the powerful forces of glacial lake outburst floods, the researchers suggested. These findings shed light on how infrequent events can shape landscapes.

A Rocky Mystery

In 2016, Marius Huber, a geoscientist at the University of Lorraine in Nancy, France, and his colleagues traveled to Nepal to solve a rocky mystery: the origin of the house-sized boulders often found in or near Himalayan river channels. "No one really knows where they're coming from," said Huber.

Boulders of that size can have a significant impact on the local hydrology, said Mike Turzewski, a geomorphologist at Pacific Lutheran University in Tacoma, Wash., not involved in the research. "They can completely change the direction of the channel."

The boulders stick out like sore thumbs not only because of their sizes but also because of their compositions—their lithologies tend to differ from those of their immediate surroundings. That's a telltale sign that they've been transported at some point in the past, the researchers concluded. But the Trishuli and Sunkoshi river channels, where the scientists did their fieldwork, are at too low an elevation to have been glaciated in the past, meaning that the rocks couldn't have hitched a ride with a glacier.

Measuring "Sunburn"

Huber and his collaborators focused on 16 boulders ranging in diameter from about 5 to 30 meters. They clambered to the top of each rock to collect samples for cosmic ray exposure dating to estimate how long ago the rocks had settled into their current positions. The technique hinges on measuring minute changes in rock chemistry, which arise when energetic protons—emitted by distant supernova explosions—slam into the boulders over time. "Cosmogenic radiation alters the surface of the rock over time," said Huber. "It's like a sunburn."

The researchers found that the boulders' ages ranged from fewer than 500 years to up to about 13,000 years. However, more than half of the rocks had ages that clustered around 5,000 years. That pattern was striking, said Huber, and informative. It meant that the boulders probably weren't being heaved by earthquakes. Repeated temblors over time—a region's earthquakes tend to strike every few hundred or thousand years—would have yielded a larger spread in ages rather than a single cluster, the researchers concluded.

Lots of Water

Huber and his team next used three different metrics to estimate the water flow velocities necessary to have moved the boulders. They found velocities in the range of roughly 4–17 meters per second, which, when translated into peak discharge values for either the Trishuli or Sunkoshi river channel, yielded values ranging from about 1,300 to 300,000 cubic meters per second. (For comparison, the Mississippi River discharges roughly 16,000 cubic meters of water per second into the Gulf of Mexico.)

That's higher than the levels associated with even monsoonal flooding, the researchers calculated. "Our discharges are considerably bigger than most monsoonal discharges," said Huber. "You need lots of water."

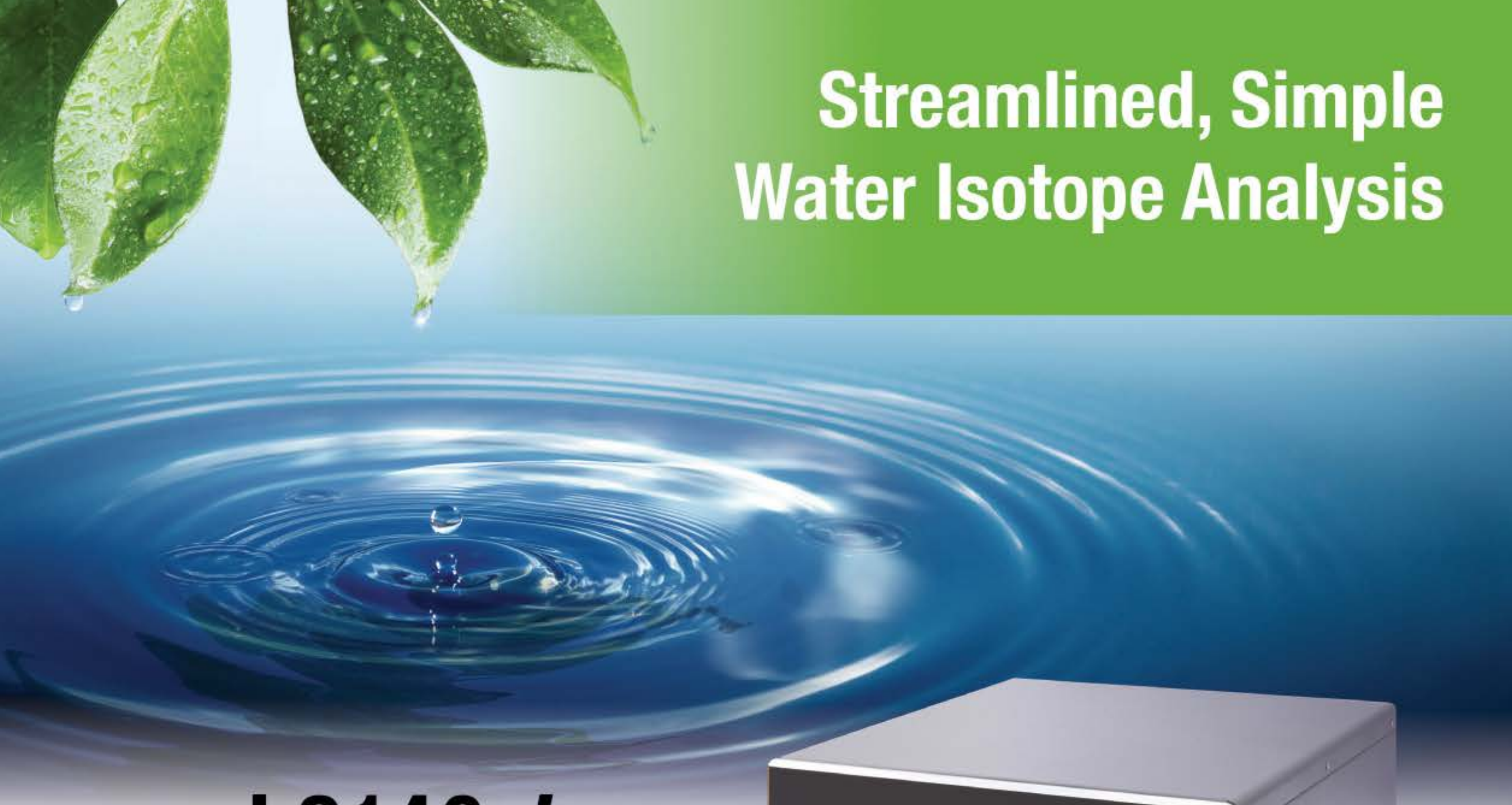
A plausible culprit, Huber and his colleagues suggested, is a glacial lake outburst flood. These events, which occur worldwide, involve the sudden drainage of a glacier-fed lake. (Many such lakes are bounded by fragile glacial moraine, which is apt to give way.) Glacial lake outburst floods have frequently struck in the Himalayas; one roared down the Sunkoshi River valley in 2016.

An uptick in glacial lake outburst flood activity roughly 5,000 years ago makes sense, Huber and his team proposed. Climate proxies such as ice and sediment cores record drier-than-normal conditions around that time, and glaciers tend to shrink when there's less precipitation, said Huber. Because receding glaciers form moraines, setting up the conditions for glacial lake outburst floods, this time period was essentially primed for heaving around big boulders, the researchers concluded. These results were published in *Earth Surface Dynamics* (bit.ly/boulder-emplacement).

It's worth returning to the Himalayas to measure more boulders in the future, said Huber. "We'll get a better picture of what's going on."

By **Katherine Kornei** (@KatherineKornei), Science Writer

Streamlined, Simple Water Isotope Analysis



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What Controls Giant Subduction Earthquakes?

The magnitude 9.1 Tohoku earthquake that devastated parts of Japan in 2011 came as a surprise because it occurred in a region that wasn't thought to be able to produce giant earthquakes. Credit: William Saito/Flickr, CC BY-NC-ND 2.0 (bit.ly/ccbyncnd2-0)

Giant earthquakes—those greater than magnitude 8.5—are rare. That's good news for people living on the coastlines along subduction zones where giant earthquakes occur but bad news for geophysicists who want to understand where and why they strike. Now a new study that models seismic activity in subduction zones has pinpointed the factors responsible for Earth's largest earthquakes.

"We have just a few hundred of these very big events over the whole history," said Andreas Schäfer, a disaster researcher at Karlsruhe Institute of Technology who was not involved in the new study. "Empirically speaking, that's not a lot of data."

To sidestep this data problem, Iskander Muldashev, a geophysical modeler at Bremen University, and Stephan Sobolev, a geodynamic modeler at GFZ Helmholtz Centre Potsdam, developed numerical models that simulate seismic cycles for subduction zones. The models showed that a shallow angle of subduction for the sinking oceanic plate and a thick layer of sediments in the trench where it meets the continental plate were the most important factors in creating a large rupture zone, leading to giant subduction earthquakes.

Earthquake Surprises

Two of the largest earthquakes (and subsequent tsunamis) ever observed occurred in the past 2 decades: the 2004 Sumatra earthquake and the 2011 Tohoku earthquake. Both had an estimated magnitude of 9.1, which surprised scientists. "No one expected such large earthquakes at those places," said Sobolev.

Influential research dating back to 1980 proposed that earthquake magnitude depended on the age of the subducting plate and the rate of subduction. Specifically, a young oceanic plate with a rapid rate of subduction was expected to produce the biggest earthquakes. But conditions at the Sumatran and Japanese subduction zones didn't fit into this classical view.

"We have just a few hundred of these very big [earthquakes] over the whole history.... Empirically speaking, that's not a lot of data."

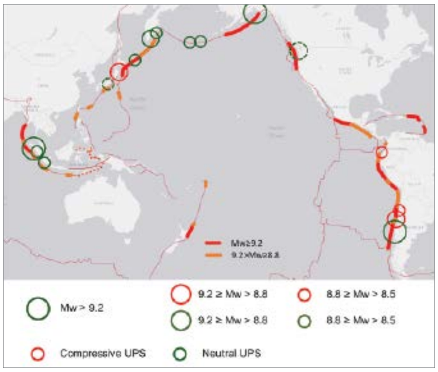
"That idea, which was wonderful in its simplicity, didn't work," said Sobolev. "So the question is, What are the controlling factors?"

In their paper, published in *Geochemistry, Geophysics, Geosystems*, Muldashev and Sobolev used a 2D cross-scale numerical model they developed when Muldashev was a graduate student at Potsdam (bit.ly/earthquake-magnitude). It simulates subduction processes on timescales of millions of years but can also zoom in to timescales as small as 40 seconds to capture the activity of earthquakes. They varied multiple factors, including subduction rates, the geometry of the subduction zone, and the amount of friction between the plates, to see which factors led to earthquakes with the greatest magnitude.

The modeling pointed to the angle of subduction of the oceanic plate as the most important factor—the flatter the dipping angle of the slab, the larger the possible magnitude of the earthquake. This is because with a shallow angle, the slab will have a longer surface within the temperature range capable of generating earthquakes, creating a wider seismogenic zone. A low level of friction in the subduction zone is also important for creating giant earthquakes, so a less rough ocean bottom or thick sediments that can smooth over a rough subducted seafloor were also critical. These characteristics allowed the rupture to travel deeper, which also increased the rupture's width.

Although the results contradict the classical view of giant earthquakes from the 1980s, they confirm findings from recent numerical modeling efforts and statistical analyses and point to the overall size of the rupture zone as the key to producing giant earthquakes.

One limitation of the study is that because of the complexity of the models and the constraints of available computing power, the model is 2D, although the researchers extrapolated the results into 3D. "These 3D models, in my view, are still stretched 2D models that don't really capture the 3D complexity of real subduction zones," said Wouter Schellart, a geodynamicist at Vrije Universiteit Amsterdam. To take the next



This map displays subduction zones predicted to generate earthquakes with maximum magnitudes of 8.8–9.2 (orange) and more than 9.2 (red). Circles show the locations of previous earthquakes with magnitudes greater than 8.5 in subduction zones. Red circles indicate compressive upper plate strain (UPS), and green circles indicate neutral UPS. Dotted circles indicate preinstrumental events. Credit: Muldashev and Sobolev, 2020, https://doi.org/10.1029/2020GC009145, CC BY 4.0 (bit.ly/ccby4-0)

step, Schellart thinks researchers should extend the models into three dimensions, taking into account variables that might affect the estimated magnitudes, such as the curvature of the subduction zone or irregularities in the plate boundaries.

What's the Worst That Could Happen?

Muldashev and Sobolev applied their findings to estimate potential worst-case earthquake scenarios for subduction zones worldwide and developed maps highlighting areas where giant earthquakes could occur. The areas align well with the locations of giant earthquakes from the 20th and 21st centuries and with similar maps based on statistical analyses of earthquake observations. The agreement suggests that the community may be getting a better handle on what controls the sizes of giant earthquakes and where they might strike. "From a scientific perspective, it is good to know that we are making progress," said Schäfer.

Muldashev cautions, however, that we still don't know enough to predict with any precision where future giant earthquakes will occur. "So far, with the tools and knowledge and the records that we have, we cannot make good predictions," he said, "but this is one step forward."

By **Patricia Waldron** (@PatriciaWaldron), Science Writer

A Little-Known Mass Extinction and the "Dawn of the Modern World"

Massive volcanic eruptions followed by climate change, widespread extinction, and, eventually, the emergence of new life forms: It sounds like the story of one of Earth's five great mass extinctions.

Now researchers say the same description applies to a lesser known—but highly consequential—event referred to as the Carnian Pluvial Episode (CPE), 233 million years ago.

Unlike some of the more dramatic mass extinctions, the signature of the CPE is difficult to trace. But working across disciplines and continents, a team of scientists has been able to piece together a broad overview, showing that it was a period of rapid biological turnover on a global scale.

The accumulated evidence, including results of a new fossil analysis, shows that the CPE was a major extinction event. More than that, however, the evidence indicates that it was a period of new beginnings. Most notably, the CPE marks the start of the dinosaurs' ascendance to ubiquity and ecological dominance.

Ecologically, the researchers said, the Carnian extinction marks the "dawn of the modern world." The new study was published in *Science Advances* (bit.ly/carnian-extinction).

Extinction and Recovery

The CPE is named for the stage of the Late Triassic in which it occurred—the Carnian—and for its signature feature: rain. A lot of rain, in four main pulses lasting over a million years, fell across much of the supercontinent of Pangaea.

The rains were accompanied by global warming and probably widespread ocean anoxia and acidification, the researchers said. All told, their analysis shows that these factors resulted in the extinction of one third of all marine species. Ecosystems on land also underwent massive transformations during and after the CPE, including the loss of dominant plant and herbivore species.

Study coauthor Mike Benton, a professor of vertebrate paleontology at the University of Bristol in the United Kingdom, said one of the team's goals was to determine the ranking of the Carnian event among other mass extinctions. "It appears not as substantial as the 'big five,' but not far off, and with proper analysis in the future it might turn out to be of similar magnitude," he said.

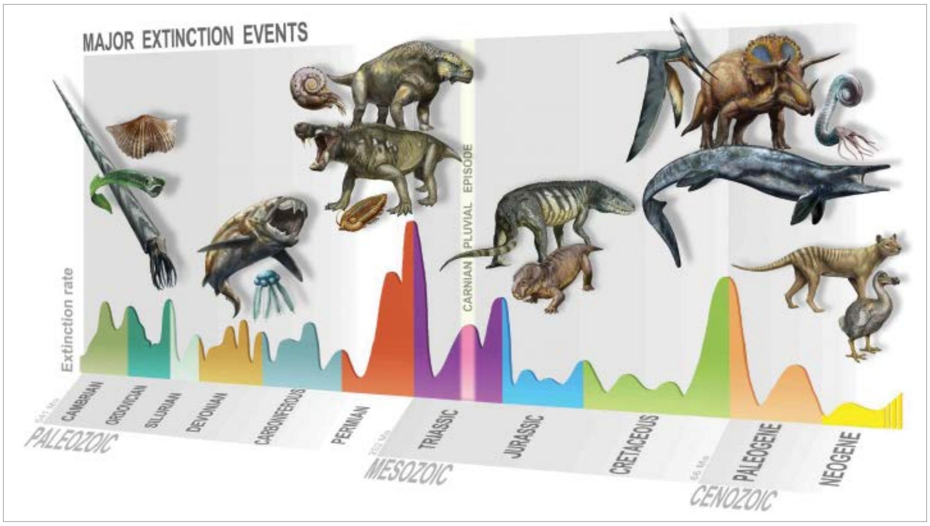
The earliest crocodilian reptiles, like Hesperosuchus, *arose during the Carnian. Credit: iStock.com/Aunt_Spray*

Intense rains, global warming, and probably widespread ocean anoxia and acidification resulted in the extinction of one third of all marine species during the Carnian.

It was an ill-timed disaster for a planet still only very slowly recovering from the biggest mass extinction of them all, at the end of the Permian period just 20 million years earlier. "The end-Permian extinction wiped out 95% of all marine species, and the Triassic was a time of recovery," Benton noted. "It now seems the CPE was a key punctuation [in that process]."

"A key feature of the CPE is that extinction was very rapidly followed by a big radiation," said lead author Jacopo Dal Corso, a geology professor at the China University of Geosciences in Wuhan. "A number of groups that have a central role in today's ecosystems appeared or diversified for the first time in the Carnian."

Benton noted that this period saw "the rise of modern reefs and plankton in the oceans and the rise of modern tetrapod groups, including frogs, lizards, turtles, crocodilians, dinosaurs, and mammals…along with some important plant groups such as conifers, and



The Carnian Pluvial Episode was sandwiched between two of the largest mass extinctions, the end Permian and the end Triassic. Credit: D. Bonadonna/MUSE, Trento

some new groups of insects." All of this innovation, he said, forms much of the basis of modern ecosystems. "Even the dinosaurs, as birds, are part of our modern fauna."

Gerta Keller, a geology professor at Princeton University who was not part of the study, said the work sheds new light on "one of the least known and underrated mass extinction events. I congratulate the authors for placing the Carnian extinction on the map with the other five big mass extinctions, among which it may eventually take its place after further investigations."

The Wrangellia Eruptions

Other mass extinctions are known to have been caused by climate change initiated by volcanism, and researchers say the same is probably true for the Carnian. During this time a series of enormous eruptions occurred in Wrangellia, then an equatorial island region off the coast of Pangaea. The Wrangellia basaltic accretions now form a substantial part of western Canada.

Researchers estimate that Wrangellia volcanism produced more than a million cubic kilometers of basalts—but that may be an underestimate because much of the volcanic rock has since been subducted. Researchers think that this release was the trigger for the climatic and biological changes of the CPE.

The new study is the first comprehensive review of the timing and global impact of the Wrangellia eruptions and their probable link to the climate episode and mass extinction. The work draws on studies from geological, paleontological, and climatological literature conducted in Europe, China, and South America. To this the researchers added a new analysis of two large fossil databases representing thousands of collections to demonstrate the magnitude of extinction and origination associated with the CPE.

"In our review we were able, through a long work of synthesis and revision of available information, to show with a high resolution the synchroneity between biological and environmental changes we observe in the rocks of 233 million years ago," Dal Corso said.

The scientists said that much work remains to more precisely uncover the scope of the Carnian extinction, its link to the Wrangellia eruptions, and possibly other volcanic events. They hope the new review will help bring the CPE to the attention of a broader research community.

"Until now," Dal Corso said, "the Carnian Pluvial Episode has been the research topic of a very small community of scientists. I think that many people were unaware of it or of its importance."

By **Scott Norris** (@norris_sd), Science Writer

How Infrastructure Standards Miss the Mark on Snowmelt

Snowmelt was one of the factors that figured into the spillway failure at California's Oroville Dam, above, in 2017. Credit: California Department of Water Resources

California's Oroville Dam holds back a reservoir that provides water for 23 million people. In February 2017, rainstorms doused the area and filled the reservoir beyond its normal capacity. Excess water was released through the main spillway, but the structure failed, and 188,000 people living downstream evacuated to avoid potential floods.

Several factors contributed to the spillway failure, and one of them was snow. Warm temperatures and rain melted much of the unusually deep snowpack in the Sierra Nevada mountains that winter, which ran off into the reservoir below.

"You wouldn't have had such a severe incident if there wasn't so much water coming into the lake that they had to let out really, really fast," said Brian Henn, a machine learning scientist focusing on global climate models at the investment and philanthropic company Vulcan Inc.

In parts of the United States, snowmelt presents a flood hazard. Although snow usually melts gradually as winter gives way to spring, if it melts rapidly because of warm spells or rain-on-snow events, the runoff into rivers can lead to severe floods. In recent years, snowmelt-driven floods have become a more urgent concern. But NOAA Atlas 14, a dataset relied on by civil engineers to design flood-resilient infrastructure, only accounts for liquid precipitation, not snowmelt.

To address this, Eunsang Cho, a postdoctoral researcher at NASA's Goddard Space Flight Center, and Jennifer Jacobs, a civil engineering professor at the University of New Hampshire, created a map that accounts for snowmelt across the continental United States (bit.ly/snowmelt-map). It shows that by not including snowmelt levels, NOAA Atlas 14 might be providing civil engineers in some regions with an inaccurate idea of flood risks.

"You look at some of the more extreme melt events, and almost all of them have occurred in the last 10 years or so, which is a warning that as things get warmer, particularly in the winter, you have the potential for added hazard from snow melting fast," said Henn. "That wasn't a hazard that used to exist when a lot of our older infrastructure was designed."

NOAA Atlas 14 works well for most parts of the country where snowmelt isn't a big concern, but for regions with heavy snowpack—like the mountainous western United States, the north central United States, and the Northeast—NOAA's values are incomplete. "That kind of information is useful, but not completely accurate," said Lai-yung Ruby Leung, a Battelle fellow at Pacific Northwest National Laboratory. "Flooding is not just about precipitation." It's also about snowmelt.

"In places where you have snowpack in the wintertime that is particularly problematic," said Leung.

Mapping Snowmelt

Knowing the hazards posed by snowmelt-driven floods, Cho and Jacobs analyzed snow water equivalent (SWE, a measure of the amount of water contained in snowpack) and snowmelt data across the continental United States. They combined SWE and snowmelt values with precipitation data to create design values, values used when planning infrastructure that needs to withstand extreme events, that could offer a more complete picture than NOAA's standard design values.

To do this, they used data from a University of Arizona SWE and snowmelt product and the national Snow Data Assimilation System, or SNODAS, data set of SWE and snowmelt across the continental United States. Combining statistical and mathematical methods, Cho and Jacobs used those numbers to map annual maximum SWE and weekly snowmelt levels.

They saw that regions with high SWE and large snowmelt events were closely linked. The mountainous regions in the western United States boasted the highest extreme SWE and snowmelt values. When they compared their map of weekly snowmelt plus precipitation levels to NOAA's precipitation atlas, they saw that in 23% of 44 states for which NOAA had the necessary data, the combined snowmelt and precipitation levels were higher than NOAA's precipitation values.

This difference means that in those areas, mostly in western, north central, and northeastern regions, civil engineers are designing infrastructure on the basis of precipitation values that might be too low. "Finding that a flood can be larger than what the NOAA map shows you means that you might have underdesigned your infrastructure," said Leung.

Cho hopes that their findings can enhance current guidelines, but for the moment, the research has limited applications and doesn't consider the changing climate. "The risk of extreme precipitation and snowmelt events is increasing as things get warmer," said Henn. Although the current study is a good starting point, "if we're designing based on data that might be 30 years old, it might already be out of date."

Cho is working on that problem and currently trying to determine how climate change will influence their values. "Based on this climate issue, the standard values should be updated regularly in the future to provide the most robust guidance for engineering or water resource management," he said.

"It's important for us to recognize that past information is not necessarily the only information that you should use for designing your infrastructure," said Leung, "because things are changing."

By **Jackie Rocheleau** (@JackieRocheleau), Science Writer

Bat Guano Traces Changes in Agriculture and Hurricane Activity

Bat guano from Jamaica's Home Away from Home Cave reveals a long history of environmental and agricultural changes. Credit: Christopher Grooms

Ice cores and tree rings are natural record keepers. Now researchers have used a complementary but potentially stinkier data set—bat guano—to peer into the past. After analyzing bits of pollen in excrement found in two caves in Jamaica, scientists believe they've pinpointed changes in agricultural production and hurricane activity.

Into the Depths

Twice in 2012, Wieslaw Bogdanowicz, a zoologist at the Polish Academy of Sciences, and his colleagues met in Jamaica. Each time, they loaded up with spelunking equipment and hiked for hours through jungle-like terrain to reach two caves. That's when the real fun began: The team put on climbing gear and rappeled tens of meters into each underground world. "It's straight down," team member Stefan Stewart, founder of the Jamaican Caves Organisation, said of one cave.

Bogdanowicz and his colleagues visited Schwallenburgh Cave in northern Jamaica and Home Away from Home Cave in the interior of the island. Both caves have been explored only a handful of times because they're so remote and require technical climbing equipment, said Stewart.

Inaccessibility Makes Good Evidence

The relative inaccessibility of these two subterranean systems is a boon to science. It ensures that their extensive deposits of bat guano—measuring over 120 centimeters thick in some places—have remained largely unmolested by humans. The excrement, with its high levels of nitrogen, is commonly mined for fertilizer, said Donald McFarlane, a cave ecologist at the Claremont Colleges' W. M. Keck Science Department in California, not involved in the research. "Many of the deposits have been destroyed."

Bat guano builds up over time thanks to roosting bats. Like ice cores and tree rings, it can provide a record of past environmental conditions. That's because guano reflects the plants, water, and insects that bats consume, the chemistry of which can shift with changing climatic conditions.

Roughly 3,000 insect-, nectar-, and fruit-eating bats occupy Home Away from Home Cave, a census conducted in 2008–2009 revealed. (The bat population in Schwallenburgh Cave hasn't yet been surveyed.) A single bat excretes about 20 millimeter-scale pellets of feces each day, and a colony's cumulative production of guano can be downright prodigious: Bracken Cave, in Texas, contains piles of guano topping 17 meters.

Scooping and Bagging

In both Schwallenburgh Cave and Home Away from Home Cave, the researchers used a metal tray to scoop out roughly 1-centimeter-thick layers of guano, which they then bagged individually. They collected roughly 80 bags from Schwallenburgh and 130 bags from Home Away from Home. It was a sizable haul of guano in total, Bogdanowicz said. "We had something like 20 kilograms of guano from each cave."

That's when the real fun began: The team put on climbing gear and rappeled tens of meters into each underground world.

Back in the laboratory, Bogdanowicz and his colleagues age dated 20 layers of guano from Schwallenburgh Cave and 28 layers from Home Away from Home Cave using a combi-

“We had something like 20 kilograms of guano from each cave.”

nation of ^{14}C dating and ^{210}Pb dating. They interpolated between the dated guano deposits to construct an age curve for each cave.

Schwallenburgh Cave’s deepest guano deposits were excreted roughly 200 years ago, the scientists found, and Home Away from Home Cave’s deposits traced back roughly 4,300 years. (Jamaica’s first human inhabitants, the Taino, arrived on the island about 2,500 years ago.)

Hints of Hurricanes

Bogdanowicz and his collaborators used a microscope to examine pollen grains and fungal spores within the guano. They found evidence of deciduous trees, shrubs, grasses, and cultivated crops like citrus, coffee, and cacao. This palynological record tracks agricultural changes, the researchers proposed. For instance, a decrease in coffee pollen in the early 19th century reflects decreased coffee production, a change most likely linked to international trade being reduced by the Napoleonic Wars (1799–1815), Bogdanowicz and his team suggested.

Guano can also imprint environmental changes like hurricane activity, the researchers proposed. Bogdanowicz and his collaborators measured a large uptick in mangrove pollen in the early 19th century, a change they attributed to two known hurricanes in 1804 that likely transported coastal vegetation inland. The scientists also noted similar increases in mangrove pollen that they suggested are due to hurricanes known to have occurred in 1903, 1909, 1935, 1951, and 1988, they reported in *Quaternary International* (bit.ly/guano-deposit).

These findings are intriguing but should be taken with a grain of salt, said Bogdan Onac, a paleoclimatologist at the University of South Florida in Tampa not involved in the research. That’s because other events, like fields being cleared for agriculture or large fires, can also manifest as changes in pollen, he said. Conclusively pinning the blame on hurricanes might be premature, said Onac. “It’s a little bit tricky just based on pollen to really, really be sure that’s the case.”

By **Katherine Kornei** (@KatherineKornei), Science Writer

Wildfires Threaten West Coast’s Seismic Network

As climate change increases the threat of wildfires, U.S. states are battling historic blazes. On the West Coast, the fires have put at risk several hundred seismic stations tasked with protecting citizens from the effects of earthquakes—nonseasonal but ever present scourges.

The network of seismic stations informs ShakeAlert, an earthquake early-warning system designed to give people enough time to drop, cover, and hold on before an earthquake’s waves roll through. Eliminating stations risks slowing these alerts.

“There is no one person tracking all seismic stations that may be affected by the fires,” said Kasey Aderhold, a seismologist with the Incorporated Research Institutions for Seismology (IRIS). Instead, several organizations oversee subsets of the network, monitoring the health of their charges by watching real-time data streams. “If data [are] coming in,” Aderhold said, “we are good. If the data connection flatlines, we investigate.”

A solar powered seismic station (station code SALT) was installed by the Pacific Northwest Seismic Network as part of its earthquake early-warning system. This station successfully withstood one of the recent wildfires that burned through Oregon, thanks to fire-armoring installation techniques, and it continues to transmit data. Credit: Sara Meyer

Vulnerabilities

Wildfires attack seismic stations directly and indirectly by excising them from the rest of the network. The sensors and electronics that record the quakes often withstand direct assaults, although Paul Bodin, a seismologist and network manager of the Pacific Northwest Seismic Network, noted that “if a fire wants to eat your station, it’ll find a way to eat your station.”

Often, the stations’ most vulnerable hardware—communications and power—may end up scorched. For example, newer stations have solar panels necessarily exposed to both sky and flame. Fire disables these stations until repairs can commence, explained Peggy Hellweg, an operations manager at the Berkeley Seismological Laboratory.

When wildfire indirectly incapacitates stations, “the telemetry is particularly fragile,” said Bodin. Telemetry refers to instruments that determine how stations communicate data in real time—by Ethernet, satellite, cell, or radio. Fires can cause cell tower outages, temporarily decommissioning any connected stations by amputating the data feed. In such a scenario, stations typically come back online when power is restored.

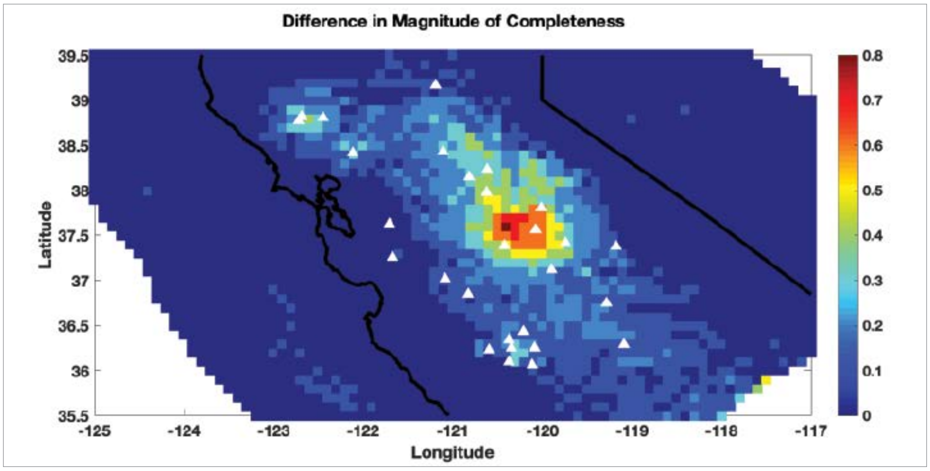
If an off-line station doesn’t reappear in the data stream, said Hellweg, “we have to visit to see what the details are.” However, sending field personnel into hazardous situations like a wildfire, especially in the COVID-19 era, is not a good option, explained Bodin.

Fewer Stations, Less Coverage

“Sometimes stations are set up to daisy-chain or wheel-and-spoke back to a communication hub, often through low-cost radio connections,” explained Aderhold. “If a key data connection is severed…then it can be problematic for seismic monitoring.”

In 2015, this scenario played out in California’s Butte Fire, where, in addition to burned stations, a swath of stations lost their hub, said Corinne Layland-Bachmann, a seismologist at Lawrence Berkeley National Laboratory. Shortly thereafter, at the request of the U.S. Geological Survey, Layland-Bachmann calculated how the loss of these stations affected the health of the seismic network using a probability-based method that determines whether the network can detect small earthquakes. She concluded that by lancing these 28 stations from the network, the fire

“If a fire wants to eat your station, it’ll find a way to eat your station.”



This image shows how the magnitude of completeness, a measure of how sensitive the existing seismic network is, changed after removal of 28 seismic stations (white triangles) because of wildfires. California's state boundary is shown by a black line. Credit: Corinne Layland-Bachmann

noticeably decreased the network's ability to detect tiny temblors, particularly in the wildfire-affected region.

For the Pacific Northwest, Bodin said, "I'm not worried about earthquake early warning and fires at this point." He explained that in Washington, fires tend to rage in the east, which is less seismically active. Also, when stations receive upgrades, they "are armored against fire." For example, replacing trees and shrubs that abut stations with gravel removes fuel for encroaching fires.

California, however, hosts fires that regularly cross active faults blanketed in dense instrumentation. "Every station missing in the network is a problem for earthquake early-warning [systems] because it will take longer to detect an earthquake with fewer stations," said Hellweg. She argued that even small, undetected earthquakes matter. "Every measurement we make of an earthquake brings us another step forward in terms of understanding how they happen, why they happen, and when they happen and will help us in our ability to forecast earthquakes."

For now, both Bodin and Hellweg agreed that they've been lucky, considering the region's historic infernos. Hellweg estimated that five to six of the stations she manages have been burned. She said, "Stations from other networks in the state have also been affected." Likewise, Bodin guessed that between two and 10 stations of the several hundred under his watch have been affected by fire. "It's a dynamic situation," he said.

By **Alka Tripathy-Lang** (@DrAlkaTrip), Science Writer

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#GeoGRExit: Why Geosciences Programs Are Dropping the GRE

A lot has changed recently in higher education. Amid the ongoing pandemic caused by COVID-19, universities and graduate schools have adapted their instruction and research activities and have faced declining revenues. These changes were forced upon programs by necessity, and they, along with negative impacts on many students from the pandemic, may continue affecting higher education in the near future by, for example, decreasing application numbers. To bolster admissions, some graduate programs are temporarily dropping the Graduate Record Examinations (GRE) as an admissions requirement. However, dropping the GRE altogether, as a step toward equity and inclusivity in graduate admissions and education, has been a longer-term battle, with many calling it #GRExit on social media.

The GRE is a standardized test used widely since the 1950s as a requirement for U.S. and Canadian graduate admissions. The earliest versions of the GRE were first tested on students at Harvard, Yale, Princeton, and Columbia in 1936, 3 decades before those universities became fully coed, with the test standardized by 1949. The test was overhauled in 2011, but research continues to show that it is not an accurate predictor of graduate school success, that scores are commonly misused and misinterpreted by admissions committees, and that the test is biased against women compared with men and against people of color compared with white and Asian people [*Miller and Stassun*, 2014]. The burden of taking the test, and the impact of low scores, limits access to graduate school for underrepresented groups [*Miller et al.*, 2019].

The geosciences are some of the least diverse science, technology, engineering, and mathematics (STEM) fields, especially at higher levels. More than 90% of geoscience doctoral degrees in the United States are awarded to white people, and there has been no significant change in 40 years [*Bernard and Cooperdock*, 2018]. Structural and social barriers result in undergraduate and graduate students from underrepresented backgrounds leaving the field, which compounds the lack of diversity at the faculty level. The lack of diversity and inclusion hurts the geosciences, excluding voices that can help solve Earth's most critical problems. Geoscience faculty must understand, acknowledge, and address individual and institutional biases to improve inclusion in our field. One simple way to improve diversity in geoscience graduate programs is to drop the GRE requirement for graduate admissions.

Why #GRExit?

First, "the GRE does not test the skill set and knowledge base to be a strong scientist," Shirley Malcom, director of education and human resources programs at the American Association for the Advancement of Science, told us recently. "Nor does it test the ability to form strong research questions, conduct research, and synthesize results for consumption by other scientists and the public." Like other standardized tests, the GRE mostly tests a person's ability to take a standardized test.

Several studies have shown that performance on the GRE is a poor predictor of graduate degree success across fields. For example, researchers tracked more than 1,800 doctoral students in STEM fields and found little correlation between GRE scores and degree completion. In fact, men with the lowest GRE scores finished their doctoral programs more frequently than those with the highest scores [*Petersen et al.*, 2018]. *Moneta-Koehler et al.* [2017] found that the GRE did not assess skills and fortitude for biomedical graduate programs: GRE scores had no predictive capabilities for who would graduate, pass qualifying exams, publish more papers, and obtain grants, or for any other measure of success.

Second, the GRE poses a significant financial burden to economically disadvantaged students. As of 2020, the test cost $205 to take and $27 for each official score sent to an institution to which a student applies. GRE books are an additional expense, and preparation courses can cost thousands of dollars. On top of these costs, lost wages from taking

> **"The GRE does not test the skill set and knowledge base to be a strong scientist."**

time off to travel to a testing center or attend classes, plus paying for childcare during this time, put an overwhelming burden on economically disadvantaged students.

Third, the GRE has been shown to effectively predict sex and race. *Petersen et al.* [2018] showed that there was "a significant gender effect" in GRE quantitative (Q) scores: Men averaged far higher scores than women, but no significant gender differences were seen in any other measure of success, including degree completion percentage. Further, *Miller and Stassun* [2014] showed that applicants from underrepresented groups also scored far lower than white and Asian people—for example, 82% of white and Asian applicants scored above 700 on the GRE Q, but only 5.2% of minoritized applicants did—meaning that if GRE scores provided an arbitrary cutoff for admissions, many underrepresented students, Asian women, and white women would not even be considered.

The #GRExit Movement Grows

In response to the shortcomings listed above, the 2019–2020 academic year saw a major increase in geosciences programs dropping the GRE from admission requirements: From May to December 2019, the number of geosciences programs that dropped the GRE or made it optional rose from 0 to 30, and as of early November 2020 that figure had risen to more than 90. The movement to remove the GRE requirement for graduate school admissions started in the life sciences. The geosciences movement built on the bioscience #GRExit movement and a crowdsourced database of programs that have abandoned the GRE. In September 2019, lead author Sarah Ledford created a similar #GeoGRExit database of programs no longer requiring the GRE, which students can reference when applying to graduate school.

Spring 2020 marked the first round of applications after many geosciences programs dropped the GRE requirement. Long-term monitoring of applicants and acceptances will be necessary to determine whether removing the GRE changes the numbers of minorities and white women in geosciences graduate programs and whether removing the GRE affects student success rates.

Initial anecdotal evidence indicates that graduate programs that removed the GRE requirement had higher overall numbers of applicants, as well as higher percentages of underrepresented applicants and acceptances. In Boise State University's Department of Geosciences, the number of applications increased substantially in the first applicant pool after the department dropped the GRE requirement in 2019. Across the multiple doctoral programs administered by the department, the total number of applicants was more than double the previous maximum and more than 4 times the number from the previous year. After the GRE was dropped, initial offers for admission and funding were balanced across gender.

In the Georgia Institute of Technology's (Georgia Tech) School of Earth and Atmospheric Sciences, the percentage of graduate applicants from underrepresented groups increased from a low within the past 8 years of 6% to 13% in 2020, the first applicant pool after the program dropped its GRE requirement. Of the applicants accepted in spring 2020, 23% were from underrepresented groups, compared with 5%–18% over the previous 8 years.

Advice on How to #GeoGRExit

Here we present some tips on how to approach the #GeoGRExit process from faculty whose departments successfully dropped the GRE.

First, arm yourself with data. Knowing and sharing the ample, peer-reviewed literature about the inequalities inherent in the test with faculty have been an important approach in convincing departments to drop the requirement. Prior to the successful faculty vote to drop the GRE by Georgia Tech's School of Earth and Atmospheric Sciences, coauthor Kim Cobb gave a presentation to her colleagues about compiled research on established biases in the GRE and how it is not a successful indicator of student success in graduate school.

Knowing and sharing the ample, peer-reviewed literature about the inequalities inherent in the test with faculty have been an important approach in convincing departments to drop the requirement.

Second, prepare for pushback. Many faculty have been using the GRE as an admissions metric for years without considering how it is removing strong candidates from their pool. Strike up conversations with these faculty informally to get a sense of their position, so you know where you are starting. Encourage dialogue among faculty to provide opportunities to catalog concerns about changes in admissions processes and evaluate whether those concerns are borne out by data.

Third, do your homework with the university as a whole. Find out whether other programs at your university have dropped the GRE; if so, they may already have built a framework that could save your department time and effort. You should be aware of your university's broader requirements for graduate admissions as well: Some schools have dropped the GRE from consideration for department-level admissions while still requiring it for the university application and thus still imposing financial burdens on applicants. (Temporary changes in admissions processes made by schools during the current pandemic might spur effective pushes for permanent university-wide changes in GRE requirements, although that remains to be seen.) It is also important to check whether the GRE is required for other elements within the application process, such as fellowships.

A Better Measure of Applicants

The graduate admissions process should move away from numerical rankings of students to more holistic evaluations of entire applications. Graduate programs need to clearly articulate what skills are required of applicants and use those as criteria for admissions. It is essential to remember that graduate students are trainees and will gain most of their research and technical skills in graduate school and beyond.

The overarching concept of holistic review, which emphasizes assessment of noncognitive skills, is receiving increased attention from graduate administrators [*Kent and McCarthy*, 2016]. Graduate programs have the opportunity to base decisions on assessments of skills and character attributes "such as drive, diligence, and the willingness to take scientific risks," as *Miller and Stassun* [2014, p. 303] put it, which research has shown are more predictive of future success in STEM workforces than GRE scores are.

There are no guidelines yet for what exactly programs should include in holistic reviews, but interviews with applicants would be very telling, as noted in the 2016 "Holistic Review in Graduate Admissions" report. Other applications criteria, like grade point average and letters of reference, should also be considered, but they can be susceptible to pitfalls. Grade point average and institutional prestige are often unconsciously weighted more than is warranted. Overreliance on reference letters is also problematic; many of the gatekeeping techniques that hinder equity and diversity are strongly reflected in reference letters [*Faulkes*, 2019]. We acknowledge that not every program has time to interview every graduate student candidate, but as with job interviews, time spent interviewing a short list of prospective students will result in selection of stronger candidates.

Implicit biases will continue to hamper the progress of underrepresented students in STEM. As an outdated, expensive, and biased test, the GRE exacerbates such biases. Not only is it irrelevant for American higher education in the 21st century, but also it arguably threatens scientific progress. Given the interdisciplinary and synthetic nature of Earth science subdisciplines like climate and critical zone science, placing emphasis on noncognitive skills has the potential to enhance diversity, inclusion, and access in the field while accelerating scientific discovery and innovation.

Implicit biases will continue to hamper the progress of minorities in STEM. As an outdated, expensive, and biased test, the GRE exacerbates such biases.

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▶Read the article at bit.ly/Eos-GeoGRExit

CONVERGING ON SOLUTIONS TO PLAN SUSTAINABLE CITIES

Climate change will exacerbate the food, energy, water, health, and equity challenges that urban communities face, but cities also have opportunities to improve sustainability and outcomes.

BY DONALD J. WUEBBLES, ASHISH SHARMA, AMY ANDO, LEI ZHAO, AND CAROLEE RIGSBEE

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Cities like Chicago, seen here, must take a holistic approach that combines social and political considerations with scientific and engineering approaches to produce workable strategies for dealing with the complex, interacting effects of climate change Credit: Buphoff, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

Climate change is imposing complex, interacting effects on every ecosystem around the world, and of course, there is more change to come. Problems associated with heat stress, food availability, energy security, air quality, water quality and availability, flooding, and sea level rise affect even the most remote areas, but these issues are amplified in urban areas [*Grimm et al.*, 2008], where many people already disproportionately experience disparities in health and economic and political equity [*Tessum et al.*, 2019].

Continuing rapid urban development will only intensify these disparities unless measures are taken to ameliorate them. At the same time, cities face additional stresses from ongoing and projected climate change [*U.S. Global Change Research Program*, 2017]. Under a high-emissions scenario called RCP 8.5 (Representative Concentration Pathway 8.5), a combination of sea level rise and the increasing intensity and frequency of extreme weather may make many cities nearly uninhabitable by the end of this century.

There is a need to connect sustainability science more fully with efforts to address equity and justice issues and with the many sectors that make up urban environs.

Recent unprecedented losses in equity, health, and life have exposed gaps in our readiness to cope with climate-related extremes today and our unpreparedness to face them in the future. Thus, there is a pressing need for convergent research that investigates paths toward urban sustainability. Many cities, including Barcelona, Chicago, New York, Paris, and Seattle, are attempting to increase sustainability through climate action plans that map out steps to reduce emissions.

However, there is a need for research that feeds into these plans to connect sustainability science more fully with efforts to address equity and justice issues and with the many sectors—such as infrastructure, energy, and transportation—that make up urban environs. Such efforts should aim to design multidisciplinary and multistakeholder networks that can collectively coproduce knowledge and information to deliver actionable research-based solutions and informed decision-making to the problems that communities of many sizes face (Figure 1). We now have a time-sensitive opportunity to achieve such a vision for the coproduction of knowledge, forming public-private-community partnerships with the purpose of attaining the United Nations 2030 Agenda for Sustainable Development.

INTERACTING SYSTEMS, UNINTENDED CONSEQUENCES

Considerable efforts have been invested in devising infrastructure-based schemes for climate adaptation and advancing urban sustainability [*Rosenzweig et al.*, 2009; *Sharma et al.*, 2016; *Zhao*, 2018]. However, sustainability-related strategies and actions must be carefully orchestrated because their effectiveness depends on combinations of social, economic, health, and climate conditions.

Strategies can also have complex socio-ecological trade-offs [*Cao et al.*, 2016; *Sharma et al.*, 2018] and may trigger unintended climatic and socioeconomic consequences [*Zhao et al.*, 2017]. For example, models indicate that large-scale implementation of cool roofs designed to reflect more sunlight than conventional roofs may reduce precipitation in urban areas [*Georgescu et al.*, 2014], potentially exacerbating water stress. Green infrastructure, which relies on plants to manage water runoff and filter and cool the air, may require irrigation and should be sited carefully. In dry-climate cities where water is already scarce—and becomes scarcer in the projected future under climate change [*Zhao et al.*, 2017]—green infrastructure's interaction with and effects on climate change are poorly understood.

Traditionally, urban planning concentrated on top-down interventions by agencies within municipal governments. However, in recent decades, there has been a push to create more interdisciplinary knowledge that considers a broader range of potential impacts. As part of this push, urban planning has seen a recent influx of "smart city" approaches that view cities as mechanistic systems composed of discrete components to be optimized individually. However, cities cannot achieve sustainability without a holistic view of the interdependencies among essential human needs (food, energy, and water); constructed urban infrastructure; associated natural systems (air, water, land, ecosystems); and social, political, and legal decisions spanning all relevant scales (individuals, neighborhoods, municipalities, regions, nations). For example, national policy can limit or enhance what is doable within a city. At the local scale, residents of a single neighborhood can delay projects by tying them up in litigation. Inadequate consideration of these interdependencies can thus result in unintended social stresses, especially for the poor.

We see the urban metabolism framework as essential for studying the complex interactions among people, constructed infrastructure, and surrounding natural systems in cities of all sizes.

Urban metabolisms, which consider the flows of materials and energy within a city and which comprise subsystems related to food, energy, and water, are a concept that takes such a holistic view. These subsystems and their associated climate challenges have been studied for several decades, but relationships among subsystems are often obscured by the discipline-bound approach of past research. We see

Fig. 1. This conceptual framework outlines a multidisciplinary, multistakeholder approach to urban sustainability.

Making science more relatable to the public may lead to more community involvement in planning for futures that consider local histories.

the urban metabolism framework as being an essential conceptual and quantitative model for studying the complex interactions among people, constructed infrastructure, and surrounding natural systems in cities of all sizes.

Generally, urban sustainability research is focused on very large urban systems. However, billions of people live in smaller communities, and although cities of varying sizes face many of the same problems amid climate change, a single solution for a given problem is unlikely to fit for all. Instead, cities require sustainability solutions involving infrastructure, technology, policy, and management that are tailored to their own vulnerable systems. This inclusiveness in research and planning will help improve the lives of people in less densely populated areas that are often neglected in conversations about sustainability.

Understanding the impacts of urban systems on the environment at local to global scales also requires considering complex and interdependent social and physical factors, which can be studied using increasingly sophisticated models. Despite advances in computing, however, many knowledge gaps still exist. These gaps involve both spatial and temporal scales, the need for improved data sets about urban land use, and the need for better and more detailed measurements of complex urban flows (e.g., meteorology, air quality, combined sewage outflows, mobility). These gaps prevent adequate estimates of the flows of energy and matter in urban systems [*Sharma et al.*, 2020]. More investments in focused scientific and engineering research could provide needed perspective on urban woes and potential solutions across scales.

NEEDED: MULTIDISCIPLINARY, MULTISTAKEHOLDER RESEARCH

Contemporary urban sustainability research requires a broad multidisciplinary methodology. Yet such research is challenging and therefore understandably uncommon. Engineers, social scientists, ecologists, and experts in the arts and humanities speak different disciplinary languages and approach the analysis of data from urban environments in different ways [*Jacobs*, 2014]. Their models, data sets, and findings are not easily coupled and integrated, meaning that potentially valuable urban tools and insights remain undeveloped.

However, system-level solutions can be better designed and produce fewer unintended consequences if we explore issues that lie at the intersections and boundaries of the natural sciences, engineering, humanities, social sciences, arts, and other disciplines. For example, such a holistic approach might have alerted Los Angeles city planners to the distressingly high costs to building owners associated with a 2013 law requiring that all buildings install cool roofs.

More specifically, the arts, humanities, and social sciences offer important pathways to and lessons for understanding urban sustainability that complement those typically followed by the natural sciences and engineering fields [*Pykett et al.*, 2020]. For example, community-based and participatory research methods can identify climate-related infrastructure, equity, and health risks associated with food, energy, and water needs. These methods can also help project future problems for residents of small and poor communities that are generally not represented in municipal decision-making.

Making science more relatable to the public may lead to more community involvement in planning for futures that consider local histories. In many cities, public history, heritage studies, and museum studies contribute to sustainability research through their connections with local people, past and present.

Communicating in ways that can overcome science and engineering language barriers and that use culturally meaningful framing is useful in relating traditions and lifestyles to current and future sustainability challenges in communities. Such approaches can focus on community priorities and concerns shared through cultural traditions in art, poetry, storytelling, music, or culinary arts and on using history to teach lessons about how people cause or adapt to environmental changes.

Each of these pathways can be vital in engaging policymakers, voters, and other community members in responding to environmental threats and participating in urban sustainability solutions. They can also lead to important insights into urban systems over a wide range of geographical and temporal scales (daily, seasonal, and long term), from the neighborhood to the metropolis and beyond.

Multidisciplinary approaches also support deep, bidirectional engagement with community stakeholders that leads to improved understanding of stakeholder concerns and priorities and to collaborations with players critical to delivering solutions. Communities of different sizes require different solutions depending on their resources, capabilities, and priorities.

Community groups and municipal leaders have direct understanding of pressing local problems and of the municipal settings in which solutions must be implemented. Individuals and enterprises in business, especially those that combine social, cultural, and environmental issues, referred to as social entrepreneurship, are also key to the success of sustainability solutions. Beyond providing insight into finance and feasibility issues, they can help drive the design, development, and delivery of scalable solutions. Moreover, nongovernmental organizations often have extensive experience working with multiple stakeholders to effect environmental change, albeit sometimes with a limited focus on urban sustainability that lacks a convergent multidimensional approach.

TOWARD CONVERGENT URBAN SUSTAINABILITY SCIENCES

Knowledge gaps in convergent urban sustainability research can be narrowed by focusing on cities as complex, multiscale, interdependent, and adaptive systems with active interactions among social, natural, and engineered systems. Such an approach should include local stakeholders, businesses, and communities. Toward this end, we propose a strategy for constructing urban research networks for convergent urban sustainability science that are equally relevant for cities of all sizes (Figure 2).

Now is the time for collaborations and partnerships spanning research disciplines, the private and nonprofit sectors, and representatives from municipalities to define holistic pathways forward to tackle critical urban sustainability challenges facing cities

of all sizes. Interactive planning and decision-making processes already exist, but they require additional multidisciplinary and cross-disciplinary interactions to be fully successful.

Investments in multidisciplinary and multistakeholder convergent research can guide urban innovations and advance sustainability on multiple fronts, both locally and globally. Together we can close the gaps between the diagnosis of climate-related urban challenges and the identification and implementation of appropriate solutions and partnerships that account for community concerns about health and equity and that are needed to ensure more sustainable food, energy, and water futures for our cities.

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Fig. 2. Following the steps in this flowchart can help lead to convergent urban research.

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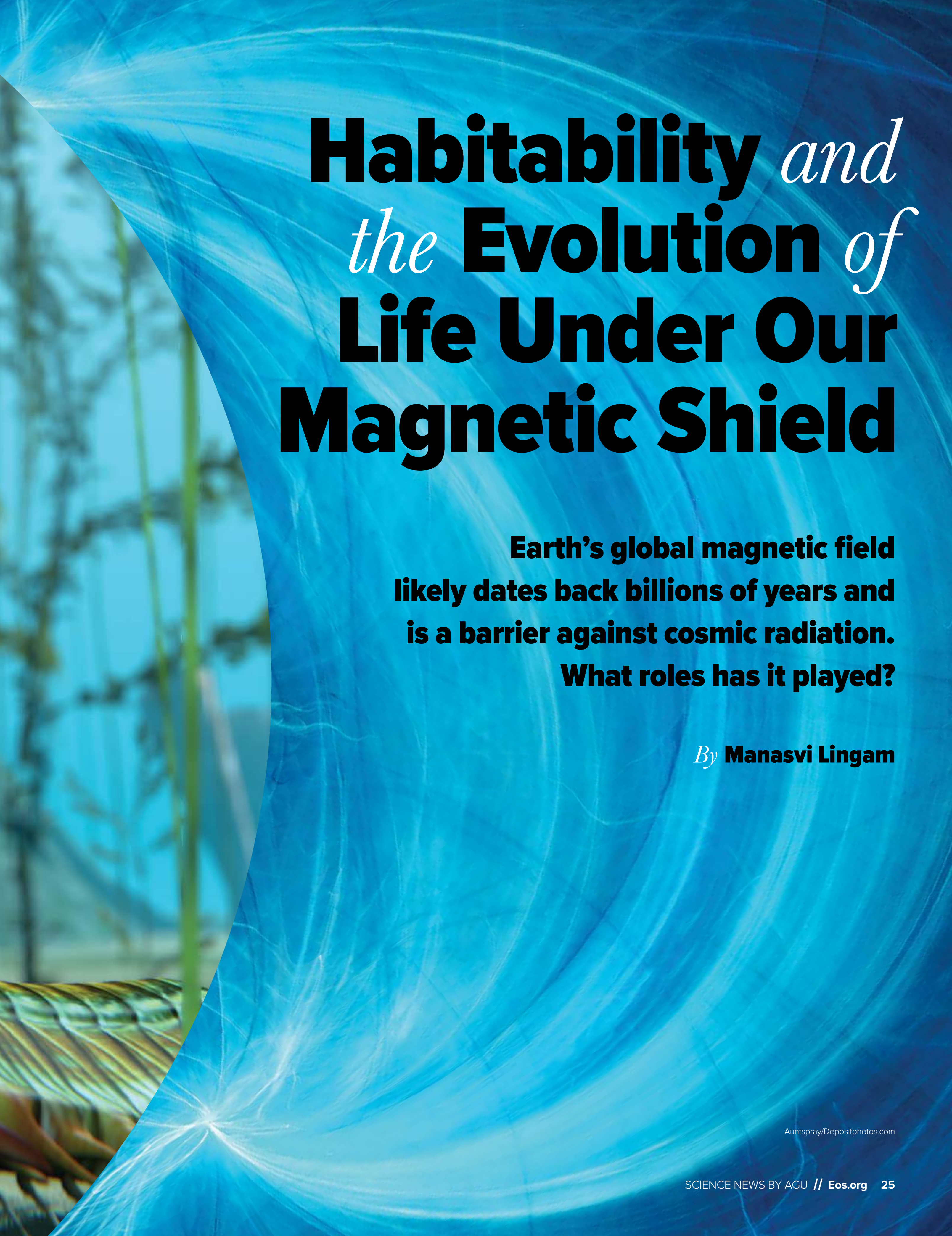

Habitability *and the* Evolution *of* Life Under Our Magnetic Shield

Earth's global magnetic field likely dates back billions of years and is a barrier against cosmic radiation. What roles has it played?

By **Manasvi Lingam**

Auntspray/Depositphotos.com

Earth's magnetic field, in some ineffable respects, is reminiscent of the exquisite poem attributed to the semihistorical Buddhist monk Budai (sometimes referred to as Hotei), considered by some to be an incarnation of the future Buddha, Maitreya:

> *Maitreya! Maitreya!*
> *Forever dividing himself,*
> *He's here, there, everywhere—*
> *Yet scarcely noticed.*
> —Hotei (as translated by Lucien Stryk and Takashi Ikemoto)

The geomagnetic field similarly permeates myriad aspects of life. For instance, a diverse range of organisms, from microscopic magnetotactic bacteria to all major groups of vertebrates, have evolved ingenious and intricate mechanisms to detect the magnetic field and to use this information for orientation and locomotion.

Humans, of course, have learned to use the geomagnetic field in countless advantageous ways, with the magnetic compass and its associated 2,000-year history as the quintessential example. On the other hand, our dependence on electromagnetic devices means that we are highly susceptible to geomagnetic storms that perturb our planet's magnetic field, with devastating economic losses potentially ranging into the trillions of dollars [*Lingam and Loeb*, 2017]. More broadly, the magnetic field generated by Earth's dynamo (the geodynamo) is responsible for our planet's substantial magnetosphere, which is believed to protect Earth against the deleterious effects of the solar wind.

The wide range of benefits stemming from Earth's magnetic field have been invoked to argue that a planetary magnetic field is a chief requirement for habitability.

The wide range of benefits stemming from Earth's magnetic field have been invoked by many scientists to argue that a planetary magnetic field is a chief requirement for habitability [*Lammer et al.*, 2009]. That Mars, a planet currently sans strong global magnetic fields, lacks a substantial atmosphere is often interpreted as a consequence of its dynamo shutting down about 4 billion years ago, which thus subjected the atmosphere to erosion by the solar wind.

Much about Earth's planetary magnetism, however, remains poorly understood. Of the multifarious questions that spring to mind, two stand out: When and how did Earth's dynamo originate and evolve over time? And what are the consequences of a magnetic field for habitability and life? Both questions span rapidly evolving research domains and touch upon many interconnected and subtle scientific issues. Hence, the discussion of them here, which offers an overview of major points, is limited and somewhat subjective in scope [*Lingam*, 2019].

The History of Earth's Dynamo

Certain minerals on Earth, such as magnetite, are particularly sensitive to the geomagnetic field because of their ferrimagnetic nature, and measurements of their magnetization have enabled us to deduce Earth's magnetic field strength at different times in the past. The oldest evidence for a geodynamo comes from analysis of magnetic inclusions in 4.2-billion-year-old zircon crystals retrieved in Australia [*Tarduno et al.*, 2020], which collectively indicate that Earth's magnetic field then may have been roughly half as strong as it is today.

This putative discovery raises more questions, including about the processes responsible for the geodynamo's genesis and functioning during the Hadean and Archean eons (spanning 2.5–4.5 billion years ago). One hypothesis, among others, suggests that the high temperatures produced during giant impact events in this period facilitated the transport of magnesium to the core, where precipitation of magnesium-containing minerals yielded enough energy to power the geodynamo [*Badro et al.*, 2016]; however, some scientists have critiqued this model on the grounds that the energy produced is insufficient. It has also been suggested that precipitation of silicon dioxide from the core may have contributed to the sustenance of the early geodynamo.

The nucleation (i.e., formation) of Earth's inner core is considered crucial in the further evolution of the geodynamo [*Smirnov et al.*, 2016], chiefly because the latent heat liberated during crystallization of the inner core, in tandem with ongoing chemical differentiation (in which materials of different compositions separate within Earth based on density and chemical affinity), is capable of powering the geodynamo. The importance of inner core nucleation (ICN) is

widely recognized, but its timing is still uncertain.

Magnetic field intensities inferred from rock samples dating to the Mesoproterozoic (roughly 1–1.5 billion years ago) have been argued as evidence for ICN occurring in this interval. In contrast, analysis of magnetic inclusions in crystals from the Ediacaran (about 565 million years ago) is compatible with the onset of ICN during that time. The discrepancy in the possible ages for the onset of ICN may stem from systematic biases in earlier paleomagnetic intensity data sets due to processes such as viscous remanent magnetization, which is induced in rocks with long-term exposure to magnetic fields, thereby making measured paleomagnetic intensities appear higher than the actual values when the rocks were formed. Chemical and thermal alteration of magnetic minerals over time can also complicate interpretations of paleomagnetic intensities.

It is tempting to speculate about whether deep connections exist between the nucleation of Earth's inner core and the increase in the strength of Earth's magnetic field on the one hand, and the diversification of animals on the other.

If nucleation of Earth's inner core occurred during the Ediacaran, a striking coincidence emerges. The Ediacaran was an unusually dynamic period on Earth, characterized, for instance, by the intermittent oxygenation of the ocean and by rapid shifts in evolution (especially in animals [*Droser et al.*, 2017]). These shifts culminated in the so-called Cambrian explosion, when multicellular life seemingly diversified into most of the lineages we recognize today. It is tempting to speculate about whether deep connections exist between ICN and the increase in the strength of Earth's magnetic field on the one hand, and the diversification of animals on the other, as suggested by some authors.

It has been proposed that the stronger magnetic field in the Cambrian was responsible for shielding the atmosphere from erosion by the solar wind, mitigating the flux of cosmic rays reaching the surface, and preventing ozone depletion. These processes might have contributed to the diversification of animals by reducing high-energy radiation and preserving oxygen levels. If proven correct, this paradigm would represent a compelling illustration of the interplay between astrophysics and biology.

Implications of Earth's Magnetic Shield

The existence of a global magnetic field raises questions about *how* it affects habitability and life. This is a question wide in scope, and the discussion here is limited to only a couple of salient effects. It is commonly thought that magnetic fields are necessary to protect planetary atmospheres from erosion by the solar wind, which hastens the acceleration and escape of atmospheric particles through electromagnetic interactions. But how valid is this premise?

Researchers have simulated the escape of oxygen ions from Earth's atmosphere by adapting a model constructed for Mars, finding that the escape rate could be elevated by a factor of roughly 1,000 if the magnetic field strength is extremely weak. However, more recent numerical models and analytical studies have found that the relationship between a planet's magnetic field and the escape rate of oxygen ions is highly nonlinear. In particular, across a range of magnetic field strengths—and contrary to expectations—the escape rate might actually *decrease* when the field strength is weakened [*Lingam and Loeb*, 2019]. Hence, there are tentative grounds to suppose that a weak or even absent geomagnetic field may not have been as much a hindrance to life as originally anticipated, at least insofar as the field's effects on atmospheric erosion by the solar wind are concerned.

There are tentative grounds to suppose that a weak or even absent geomagnetic field may not have been as much a hindrance to life as originally anticipated.

Earth's magnetospheric shielding acts as a protective barrier against high-energy solar particles and galactic cosmic rays (GCRs) (only the latter are considered here, as the former are more intermittent). When GCRs pass through Earth's atmosphere, they lead to formation of secondary particles like muons and pions. And when GCRs and their derivatives reach the surface, they can damage biomolecules like DNA. The cumulative impact of such radiation is measured by a quantity known

as the equivalent dose rate. With a weaker magnetic field, the equivalent dose rate is anticipated to increase because a higher flux of GCRs reaches the surface, and vice versa. This trend is indeed borne out by state-of-the-art numerical simulations, but the amplification is modest [*Glassmeier and Vogt*, 2010]: For an Earth-like atmosphere, the equivalent dose may only increase by a factor of about 2 if the geomagnetic field is absent.

Incoming high-energy particles also affect life through an indirect, but important, avenue. They can react with the two most abundant constituents of Earth's atmosphere, forming nitrogen oxides that subsequently react with and deplete stratospheric ozone. Ozone depletion enhances the flux of UV radiation to the surface, which has a number of well-known deleterious consequences for life, ranging from damaged biomolecules to acute physiological stress. Multiple numerical models indicate that a weakened or absent magnetic field could result in a 20% or greater increase in UV radiation penetrating to the surface, especially at the polar regions [*Glassmeier and Vogt*, 2010]. Whether such a boost, which may not sound like much at first glance, is high enough to cause widespread damage to our planet's biota is unclear given the complexity of Earth's biosphere and its nonlinear interactions with the lithosphere, hydrosphere, and atmosphere.

Fathoming the magnitude and nature of these repercussions necessitates further research synthesizing knowledge from geology, astronomy, plasma physics, microbiology, evolutionary biology, and other disciplines.

Resolving the Riddle

There is promising evidence that Earth's geodynamo initiated as early as 4.2 billion years ago and that the crystallization of Earth's inner core, which paved the way for the geodynamo of today, occurred more than half a billion years ago. Although the changes in Earth's magnetic field wrought by these transitions were likely profound, the concomitant effects on our planet's biosphere are much less clear. Earth's organisms must have been affected to some degree, but fathoming the magnitude and nature of these repercussions necessitates further research synthesizing knowledge from geology, astronomy, plasma physics, microbiology, evolutionary biology, and other disciplines.

By resolving the riddle of whether Earth's magnetic field played a significant role in modulating the evolution of life, we will be better positioned to consider the related question of whether a magnetic field is necessary for a planet to be habitable in the first place. This endeavor has major implications for understanding the origins and evolution of life on Earth; for applications, such as the development of artificial magnetospheres, that could affect humanity's future in many ways; and for addressing that age-old question, Are we alone? Let us pursue this quest in all earnestness.

By resolving whether Earth's magnetic field played a significant role in modulating the evolution of life, we will be better positioned to consider whether a magnetic field is necessary for a planet to be habitable in the first place.

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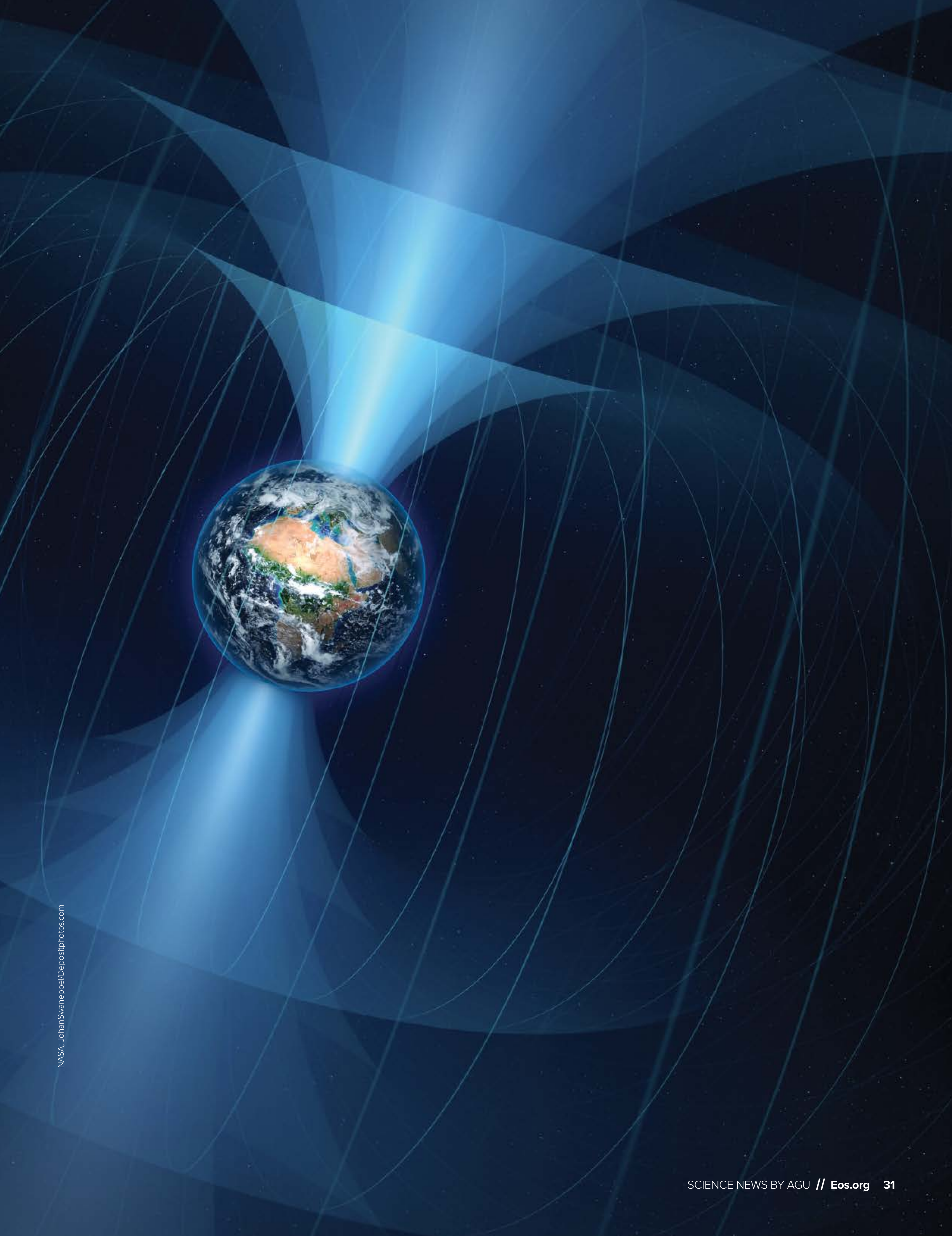
THE HERKY-JERKY WEIRDNESS OF EARTH'S MAGNETIC FIELD

Dented, erratic, and wandering, our field is constantly changing its mind.

BY JENESSA DUNCOMBE



NASA; JohanSwanepoel/Depositphotos.com

Most people don't know that Earth's magnetic field has a weak spot the size of the continental United States hovering over South America and the southern Atlantic Ocean.

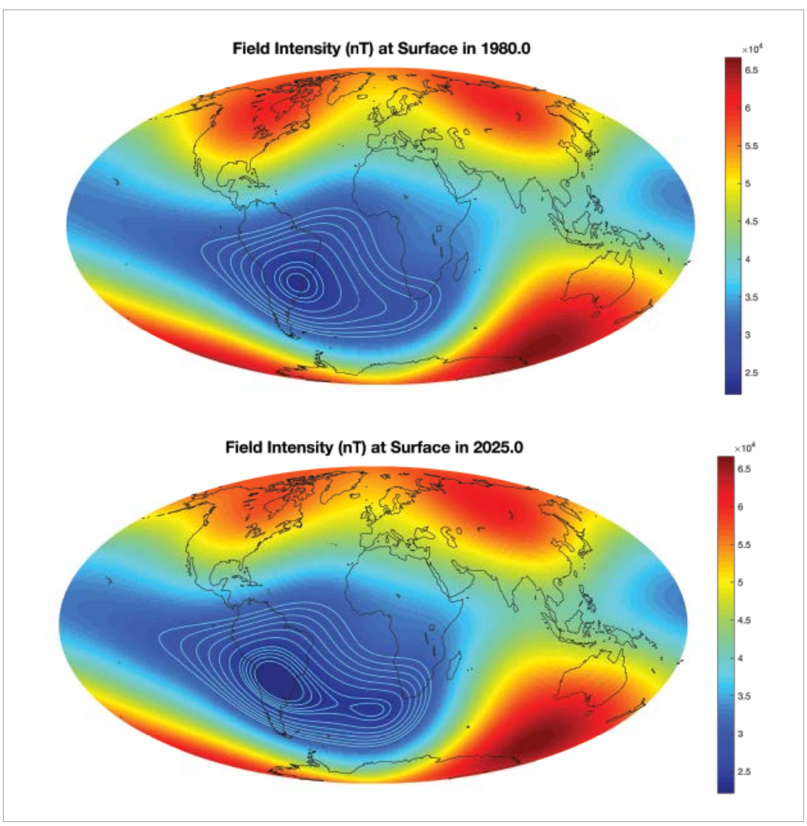
We're safe from any effects on the ground, but our satellites aren't so lucky: When they zip through this magnetic anomaly, they are bombarded with radiation more intense than anywhere else in orbit. There is reason to believe that this dent in the magnetic field, called the South Atlantic Anomaly, is only getting bigger.

This anomaly is far from the only unusual feature of Earth's magnetic field.

Hundreds of times in Earth's history, our magnetic field has reversed, switching north and south in a planetary flip-flop. Earth's magnetic North Pole keeps drifting too, stumbling around the Arctic in a chaotic dance. And scientists have detected pulses of Earth's magnetic field—called geomagnetic jerks—that can undermine our navigation systems.

Yet forecasting these changes remains a challenge. "Just like weather forecasts, you can't predict the evolution of the core beyond a few decades," said Julien Aubert, a researcher at the Paris Institute of Earth Physics.

But scientists want to know how Earth's magnetic field will change further into the future than that. Without a magnetic field, satellites could be lost, and tools that rely on careful magnetic models for navigation could go askew.



The South Atlantic Anomaly currently covers parts of southern Africa, much of the southern Atlantic Ocean, and South America. In 5 years, the region is forecast to grow and bifurcate. Credit: Weijia Kuang and Terence Sabaka/NASA GSFC

The answers can't come soon enough. The magnetic field protects Earth's atmosphere from harmful radiation emitted from the Sun. Scientists are learning that the Sun is capable of emission events—solar flares—even more destructive than we ever thought possible, and understanding our magnetic field strength and variation is vital for knowing how at risk we could be from the next big solar storm.

THE IRON HEART

The puppeteer that drives the magnetic field is Earth's core, the superheated heart of our planet, which burns as hot as the surface of the Sun.

In the core, molten metals are constantly in motion as hot buoyant plumes of lighter material rise outward. At the very center lies a small hardened inner core that has been growing as Earth cools.

This planetary anatomy sets the stage for an active magnetic field. The core's constant need to cool itself, and thus convect, drives our planet's electric generator. The generator produces a self-sustaining magnetic field through a process called the geodynamo. The mathematics of the geodynamo are so messy that Albert Einstein did not believe the theory when one of its founders, Walter M. Elsasser, proposed it to him.

The geodynamo works because the natural convection of the liquid core pushes metals through a weak existing magnetic field, exciting an electric current. Because of the relationship between electricity and magnetism, the current produces a second magnetic field, and the process repeats. This process has been self-sustaining for most of Earth's history.

Although the core sits thousands of kilometers beneath our feet, the magnetic field it produces stretches far into space, surrounding the planet like armor. But our planet's armor isn't perfect, and the results can be heartbreaking.

A CHINK IN EARTH'S ARMOR

On an early spring day in 2016, teams of engineers in Japan watched as their prized satellite spun out of control.

The teams behind Hitomi, a satellite launched just 5 weeks earlier, had hoped the spacecraft would observe black holes, galaxy clusters, and other high-energy features. The satellite even had a prized X-ray calorimeter, a triumph of 3 decades of engineering.

But a cascade of events that began with encountering the South Atlantic Anomaly seemed to spell doom for Hitomi. Passing through the anomaly, the onboard system that controlled the satellite's orientation glitched while it was pivoting to observe a new star cluster. The maneuver kicked off a series of software errors that left Hitomi spinning madly. Before long, the satellite broke into 11 pieces.

"It's a scientific tragedy," Richard Mushotzky, an astronomer at the University of Maryland in College Park, told *Nature* at the time.

Other spacecraft have fallen prey to the South Atlantic Anomaly. The magnetic field intensity at the altitude of many satellites is half as strong in the anomaly compared with elsewhere, and the weak field does not repel radiation as effectively. The inner Van Allen radiation belt, a doughnut-shaped disk of radiation around Earth that traps high-energy particles, hugs much closer to the surface at the anomaly because of the weakened field.

Any satellite in near-Earth orbit—a common altitude for Earth observing satellites—must travel through the anomaly. The Hubble Space Telescope spends 15% of its life in the region—and routinely shuts down its light-sensitive cameras to avoid damage. Some instruments, like NASA's Ionospheric Connection Explorer, power down electrical components of an ultraviolet photon detector every time they pass through. In the early days of the International Space Station, the anomaly would crash astronauts' computers.

But sometimes a satellite is just unlucky. Ashley Greeley, a postdoctoral scholar at NASA Goddard Space Flight Center, recalled a CubeSat that died shortly after launch. During start-up checks and the commissioning phase, "we think that an energetic particle hit it in the wrong place at the wrong time, and we never got data, unfortunately," she said.

A GROWING ANOMALY

Researchers discovered the South Atlantic Anomaly in 1958 when satellites first began measuring radiation in space. Now the region shows up prominently in most models, said NASA's Terence Sabaka. "Everybody is pretty much in agreement on its size, shape, and strength." Although it's still a matter of speculation, there is some evidence that the anomaly has been around since the very early 19th century and maybe even earlier.

The real debate surrounds what the anomaly will do next.

Greeley took her first look at the anomaly during her doctoral work. Peering through 20 years of satellite data, she calculated the extent of the anomaly during each pass of the Solar Anomalous and Magnetospheric Particle Explorer. Satellites in low Earth orbit pass through the region every week or so, and the transit lasts for several minutes, she said.

Over time, Greeley found that the South Atlantic Anomaly is moving westward (at about 1° longitude every 5 years) and ever so slightly northward. Eventually, "the bulk of it will be over land," she said. The bull's-eye of the anomaly will pass over Argentina, Bolivia, Brazil, Chile, and Paraguay.

A forecast from NASA scientist Weijia Kuang and University of Maryland, Baltimore County professor Andrew Tangborn shows that in addition to migrating westward, the anomaly is growing in size. Five years from now, the area below a field intensity of 24,000 nanoteslas (about half the normal magnetic strength) will grow by about 10% compared with 2019 values. The dent may also be splitting, Kuang said, or perhaps another weak spot is emerging independently and biting into it.

Although the dent is projected to grow in the next 5 years, it's impossible to make predictions further into the future, said Kuang. Fluid movement in Earth's core is so turbulent that a small perturbation to the system could lead to a cascade of outcomes that we can't foresee. The further you go in time, the more runaway situations abound.

Although the future is uncertain, studying the anomaly "provides a very good window for us to understand not only the core dynamics," said Kuang, but also "the regional properties of this area."

Luckily, the anomaly can't hurt life on the surface, said Kuang. "But if it continues to weaken over time, this may eventually impact us." The hole in our field would expose us to high-energy particles that could surge power grids and eat away at protective gases in our atmosphere.

> Jerks may illuminate the core's thermal properties, a hotly debated topic that affects our ideas about everything from the age of the core to the onset of plate tectonics.

MAGNETIC SHUDDERS AND A WANDERING POLE

Chengli Huang's daughter would often hear a familiar story at bedtime.

One day, four blind men decided to go to the zoo to visit an elephant. They'd never met one before, and they wanted to know what it looked like. The first man approached the elephant, felt its trunk, and declared it a "curved paddle." The second touched its tail and concluded it was like a stick. The third man gingerly patted the body and pronounced that the animal looked like a wall, whereas the fourth felt its leg and said it was like a pillar.

Separately, the four men understood only one part of the elephant. But together, they had a clearer picture of the elephant's true nature.

Huang tells this story to colleague Pengshuo Duan, too. As astronomers peering into Earth's interior, there is no way for them to "feel" the true nature of the core. But they can probe different aspects and collaborate and compare with others to make a more complete picture.

Scientists have long been on this quest, sometimes with fatal consequences. Explorers of old perished trying to set up monitoring stations in far-flung locales, like the doomed English explorer Sir John Franklin, whose expedition to take magnetic observations of the North Pole in 1845 ended with 129 men dead and two ships lost.

As soon as long-lasting ground observatories sprung up around the world, scientists noticed strange deviations in the field, including for example, that our magnetic North and South Poles roam freely around the

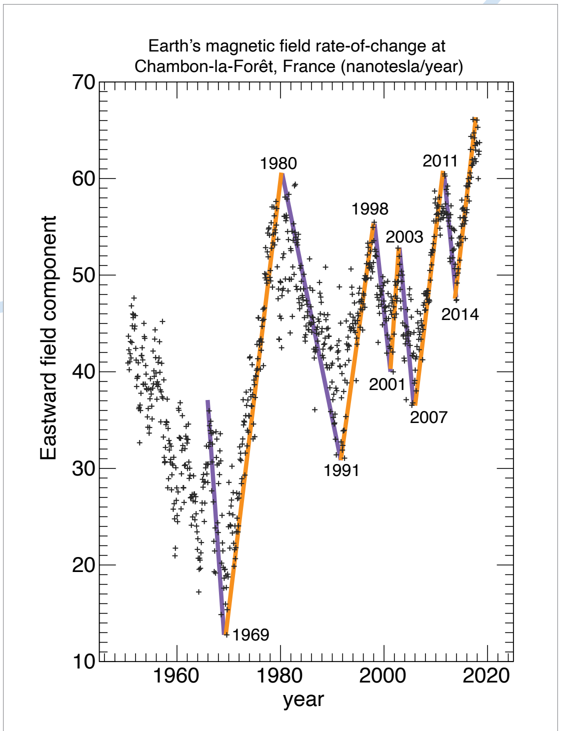
planet. It's true that the poles sit off-kilter to Earth's rotational axes because of the uneven and turbulent flow in the core, but they also drift gradually as the core's dynamics swirl field lines. Last century, the magnetic North Pole paraded through the Canadian Arctic, and since the 2000s, it's been sauntering across the Arctic Ocean.

But occasionally, this gradual movement accelerates seemingly at random, and the drift of Earth's magnetic field skirts in another direction. These diversions are called geomagnetic jerks.

The dent may be splitting, or perhaps another weak spot is emerging and biting into it.

Scientists also call the jerks "V-shaped" events based on their appearance in plots of the field's rate of change over time. The events usually last between 1 and 3 years, and the first documented case was recorded in 1902. Dozens of jerks have happened since.

The last jerk was in 2016, when it jostled the field and dramatically shifted the North Pole drift. The event was rather inconvenient because scientists had just issued a 5- year model of Earth's magnetic field called the World Magnetic Model (WMM). The WMM team had to update the model ahead of schedule to avoid unacceptable navigational errors.



You can spot jerks in the V-shaped graphs of the magnetic field's change in direction over time. Credit: Julien Aubert, IPGP/CNRS from French BCMT data

Although the origin of jerks is a subject of active research, a recent study in *Nature Geoscience* by Aubert and Chris Finlay at the Technical University of Denmark suggests that jerks may originate from the push and pull of forces in Earth's interior (bit.ly/jerks-research). When a hot plume shoots up through the outer core, the delicate balance between planetary, rotational, and electromagnetic forces careens out of whack. The off-balance forces send a shudder along magnetic field lines in the form of waves.

The next jerk may already be under way. A recent analysis by Huang and Duan predicted that the next event would occur in 2020 or 2021.

If that's the case, scientists may need to update magnetic maps on which industry and government activities rely. Companies drilling for oil and gas, for example, use fine-tuned magnetic models to dig boreholes. But not all jerks cause directional changes, so time will tell what the outcome will be.

It's too soon to know whether a jerk is happening right now, however. Finlay, part of a group that publishes magnetic field models every 6 months, said it's impossible to identify geomagnetic jerks until well after they've happened because researchers must look at the data over time. It would take about 2 years to know for sure, Finlay said.

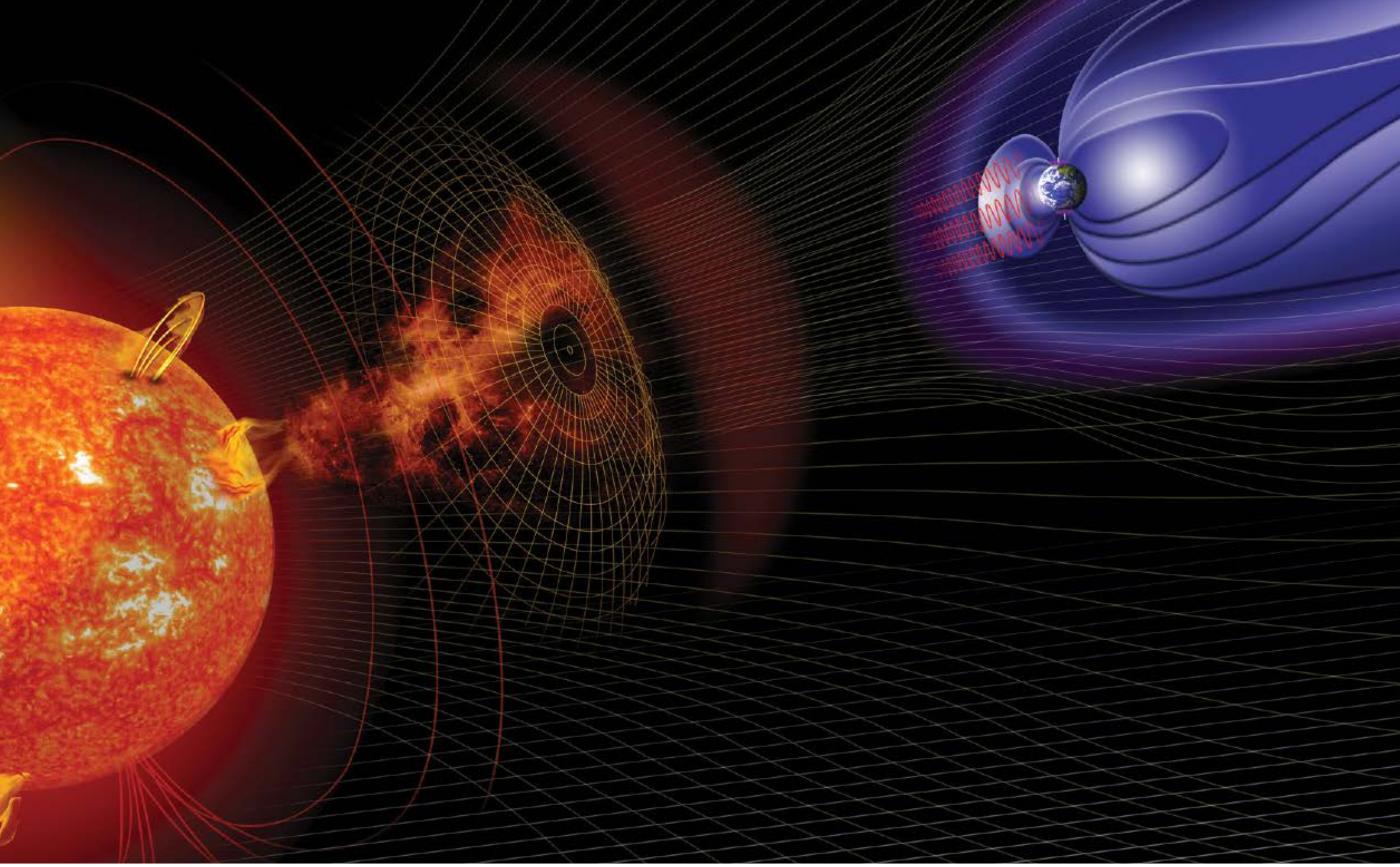
Regardless of whether the next event is upon us, geomagnetic jerks are one part of seeing the "elephant" of Earth's magnetic field. Jerks may illuminate the core's thermal properties, a hotly debated topic that affects our ideas about everything from the age of the core to the onset of plate tectonics.

Solving the mystery of the jerk's origin will remove a "stumbling block" of future magnetic field predictions, said Aubert, something we'll sorely need to better understand our planet's protective armor.

AVOIDING DOOMSDAY

Vladimir Airapetian does not mince words when it comes to apocalyptic scenarios and our magnetic field.

In one grim scenario, a catastrophically massive solar flare envelops Earth and knocks out the ozone layer, exposing us to damaging ultraviolet radiation known to cause cancer. In the 6–12 months it would take to rebuild our ozone layer, we'd live like "nocturnal animals," Airapetian said.



An artist's rendering shows a solar flare leaving the Sun and hurtling toward Earth. Credit: NASA

"You'd have to go underground and go out during the nighttime," said Airapetian, a NASA scientist at the Goddard Space Flight Center. "That's the Hollywood-type scenario."

Tales of our field catastrophically failing are part of the lore of working on Earth's magnetic field. People always want to know, "When is the really, really bad stuff happening?" said Aubert.

Although the prevailing science suggests that these doomsday scenarios are possible, they are highly unlikely. Earth's magnetic field is fickle, cratered, and ever changing, but scientists have no reason to believe that the field won't protect us for decades—and most likely centuries—to come.

Even one of the most dramatic of the scenarios, a magnetic reversal, is implausible in the foreseeable future. The last reversal occurred 780,000 years ago, and over the multibillion-year lifetime of the magnetic field, researchers guess that the poles have switched hundreds of times.

But scientists have no compelling evidence to suggest that a field reversal is upon us, said Catherine Constable, a scientist at Scripps Institution of Oceanography who studies magnetic reversals. The field changes so gradually that we'll have fair warning, at least a few decades, Constable said.

Perhaps the more worrisome danger comes from space. The magnetic field is our main line of defense against the onslaughts of high-energy particles from the Sun. Recent research by Airapetian suggests that gigantic solar flares are possible in our solar system. Observations of other stars similar to the Sun reveal that our Sun may be capable of shooting out a flare of epic proportions.

The next jerk may be already under way.

Congress passed PROSWIFT (Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act) in 2020 to pour money into space weather research, which the act's authors called a matter of national security. Heliophysics is the smallest division at NASA, so Airapetian is "so excited" for the additional funding and support to discover what space hazards lie ahead.

Until then, our magnetic field will continue to do what it does best: drift, shiver, and morph into its next grand configuration.

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Eos thanks Weijia Kuang, who generously provided a forecast of the South Atlantic Anomaly upon request.

▶ **Read the article at bit.ly/Eos-magnetic-weirdness**

A FIELD GUIDE TO THE MAGNETIC SOLAR SYSTEM

Not all planets move the needle. But whatever planet you take a magnetic compass to, it's sure to point out clues to secrets underfoot.

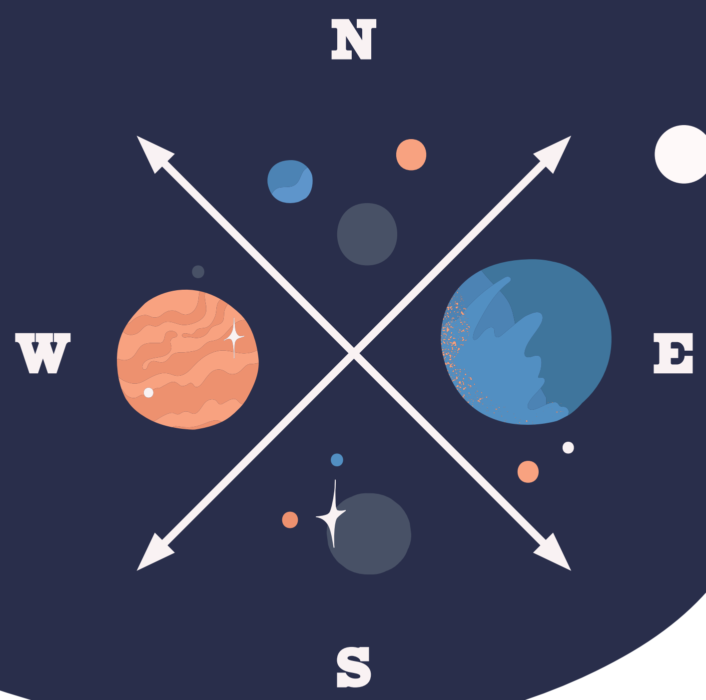
By Bas den Hond

Congratulations! With the IP9, the new interplanetary model in *Eos*'s signature line of magnetic compasses, you've chosen a travel companion that will serve you as best it can on the many GPS-challenged bodies of our solar system—be your plans a hike on Mercury, a ride on Mars, or a glide over Neptune.

Before you start using your compass, please note that your warranty is voided when you drop your IP9 onto a hard surface or into a high-pressure or high-temperature environment, or store it unshielded from magnetic fields during extended periods of interplanetary travel.

Other warnings and pointers, specific to select extraterrestrial destinations, are as follows.

Good Studio/stock.adobe.com



Bruce Buffett, of the Department of Earth and Planetary Science at the University of California, Berkeley, agreed. Models, he said, are characterized by how the friction forces associated with viscosity compete with the Coriolis forces associated with the rotation of the planet. "When we first started [modeling], the viscous forces were about 1,000 times less important than the Coriolis forces. In a realistic model, they are 10^{15} times less. In our current models, 10^5 or 10^6 is possible."

Achieving realistic conditions means that modelers like Buffett and Stanley need computers that are about 2,000 times faster than what they can currently get their hands on. If Moore's law, which says computer power doubles roughly every 2 years, keeps working, scientists will get those computers in 11 years.

In the meantime, researchers studying Mercury's magnetic field have to work with approximations, which "do produce magnetic fields," said Buffett. "There are some people who believe that if you go to lower viscosity, you stay in the same dynamical regime, and others say there could be something different, a change of phase almost. I'm not sure who's right. But the results that we are getting now are useful."

Destination: Mercury

On Mercury, using the compass will be straightforward. The structure of Mercury's magnetic field is much like Earth's, so your compass will behave approximately as if a huge bar magnet rests at the planets center, aligned with its rotational axis. Or—a bit closer to the mark—as if electric currents are girding that axis.

Do give your needle time to adjust. Mercury's magnetic field, which was measured by the MESSENGER (Mercury Surface, Space Environment, Geochemistry and Ranging) spacecraft that orbited the planet from 2011 to 2015, is only 1.1% the strength of Earth's.

And pay attention to space weather: "Because Mercury is much closer to the Sun," said Sabine Stanley, a professor in the Department of Earth and Planetary Sciences at Johns Hopkins University, "and because the planet's magnetic field is much weaker than Earth's field, there are times when the solar magnetic field gets really important, even very close to the planet. Your compass may actually measure fields in the magnetosphere of Mercury that are caused by interaction with the solar wind. We call them external magnetic fields because they are due to currents flowing outside of the planet, not inside of it."

In rocky planets like Mercury and Earth, any such internal electric currents flow in the iron cores they obtained when they were young and hot, and their materials separated out according to density.

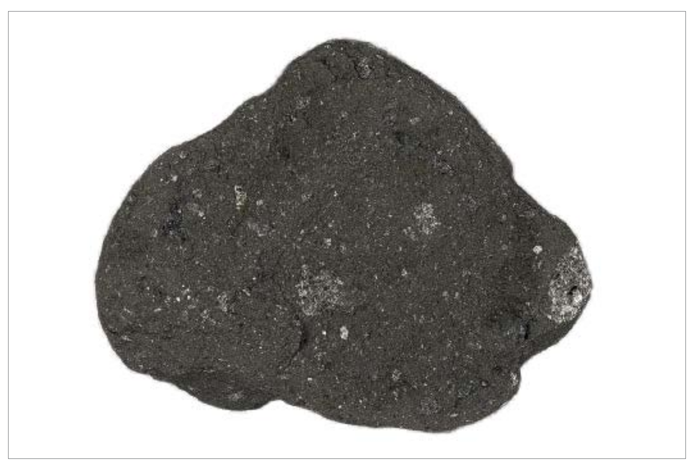
"The biggest thing Mercury's field tells you is it has an iron core, and that core is still partly liquid and moving around," said Stanley. "Before we can really understand what the field tells us about the planet, we need to understand what the composition is of the core, what's mixed in with the iron, what are the temperatures. We learn a little bit about that from the composition of the surface."

Those assumptions about composition eventually go into modeling, which is what Stanley does. The goal is to predict how an iron core, wholly or partially fluid, sheds its primordial heat. If this happens fast enough, convection will occur. As swirls of electrically conducting fluid both create and are moved around by magnetic fields, they become a self-sustaining source of such fields: a dynamo. But modeling that process realistically is not really possible just yet, said Stanley. "Because the viscosity of the iron is so low, the flows are turbulent at a small scale, so in our simulation we would really need high resolution, a lot of grid points."

Destination: The Moon

Although all major rocky bodies in our solar system have iron cores, your IP9 compass is unfortunately not suitable for use on Venus and the Moon and is of only limited use on Mars.

The time when the Moon had a global magnetic field is long past. Your compass will at most pick up remanent magnetization in some lunar rocks.



Rocks like the Contingency Sample, above, the very first sample picked up from the Moon, provide clues to the Moon's magnetic past. Credit: NASA/Astromaterials 3D

That the field is absent tells us that the lunar core is fairly quiescent, said Sonia Tikoo, an assistant professor of geophysics at Stanford University.

The ages of magnetized rocks constrain the time when a dynamo was active inside the Moon. But there are large uncertainties to those constraints, due to the limited samples of rocks that Apollo astronauts brought back to Earth.

"At least prior to 3.5 billion years ago, the field appears to have been as strong as Earth's," Tikoo said. "After that it was an order of magnitude weaker. It lasted at least until 1.9 billion years ago, and very likely was turned off by 0.9 billion years ago."

These numbers pose hard questions for modelers. The early magnetic field seems too strong to have been generated by the sort of dynamo the Moon's heat budget could sustain. "So people are looking at alternatives that are mechanical in nature," Tikoo said.

One possible energy source is precession, with the core and mantle, and perhaps a liquid outer core and a solid inner core, rotating around different axes. "That can generate turbulence in the fluid core and power a dynamo," said Tikoo. "But what is missing is any magnetohydrodynamic simulation. Nothing yet has been published that says, 'Yes, you can do this.'"

Destination: Venus

For Venus, information about any past magnetic field is even scarcer. "We don't know what we would see your compass do," admitted Joe O'Rourke, an assistant professor in the School of Earth and Space Exploration at Arizona State University. "One possibility is that it would do nothing, because there never was a magnetic field of any kind. The second is that it would occasionally behave erratically as you encounter regions of the crust that are magnetized."

Such regions would prove that Venus did have a magnetic field and that it was preserved in rocks. But whether those rocks exist is anyone's guess. "The mission that provided the tightest constraints on the magnetism of Venus was the Pioneer Venus Orbiter, which launched in the late '70s," said O'Rourke. "All we really know is that if there is a magnetic field at Venus, it has to be 100,000 times weaker than Earth's magnetic field."

The most likely explanation for the absence of a magnetic field now, according to O'Rourke, is that the Venusian lithosphere is not broken up into wandering continental plates. "Because there is no plate tectonics, [Venus's] silicate mantle probably cools down slowly, and the mantle is what is insulating the core. So Venus could have a core that is exactly the same size, exactly the same composition, as Earth, but cooling down more slowly over time."

Venus could also differ from Earth in radical ways that would reduce the strength of its magnetic field or prevent it from having one at all. A chemical gradient in the core, for instance, or an insulating ocean of molten rock surrounding the core may prevent convection in the planet's interior.

If Venus never had a magnetic field at all, it would be a very special planet indeed. Research on the remanent magnetism of meteorites suggests that even some planetesimals, the building blocks of planets like Earth and Venus, had iron cores that for a time produced dynamos.

Stanley has studied a class of very old meteorites called angrites. "They're dated very close to the beginning of the solar system," she said, "and they have a magnetic signature in them that seems to suggest they formed on a body that had a dynamo. Nothing else, like solar wind or flares, is strong enough [to form the magnetic signature]. And the field has to be very stable, for about tens of thousands of years, because rocks cool very slowly, and they imprint an average field over that time."

"So we did some modeling to ask the question, Could a planetesimal, something that's maybe 100 kilometers to a few hundred kilometers in radius, generate a dynamo?" Stanley continued. "And we found that yes, in certain circumstances you could have enough power available to generate those motions you need in the cores of these planetesimals."

That power would have come from a radiogenic isotope of aluminum, Al-26. "It has a very short half-life," said Stanley, "so all of it has already decayed today, but very early in the solar system it was an available heat source."

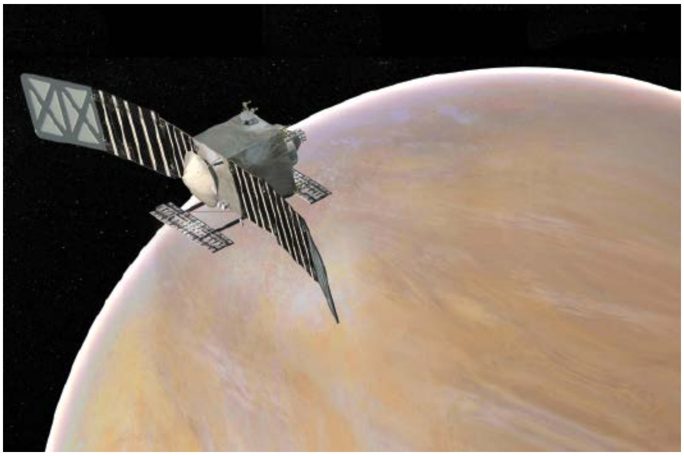
The decay of Al-26, according to Stanley's calculations, could completely melt a planetesimal, allowing an iron core first to form in its center and then to cool down through convection, creating a short-lived dynamo.

Many planetesimals are still around, for instance, as Kuiper belt objects, and two have been visited by a spacecraft: the contact binary Arrokoth and the dwarf planet Pluto. When New Horizons came calling, however, it didn't bring a magnetometer. Its designers didn't think such an instrument would measure anything while passing Pluto. Pluto's small size and slow rotation—its day takes almost an Earth week—work against any dynamo activity. Stanley is quite sure: "Pluto does not have a magnetic field."

Whether Venus ever had a dynamo can be established only by a new magnetometer-equipped mission.

O'Rourke hopes the recent discovery of phosphine in the Venusian atmosphere will be an impetus to go there again. "Just the fact that we don't understand fundamental things about Earth's nearest neighbor is humiliating to our attempts to claim that we understand anything about planetary evolution.

"IF THERE IS A MAGNETIC FIELD AT VENUS, IT HAS TO BE 100,000 TIMES WEAKER THAN EARTH'S MAGNETIC FIELD."



The VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy) orbiter, seen here in an artist's rendering, is one of many proposed missions to Venus.

THE NEXT MARS MISSION WILL ARRIVE IN FEBRUARY WITH A ROVER, PERSEVERANCE, BUT WITHOUT A MAGNETOMETER.

There have been many great mission proposals for Venus that are technically ready, they're scientifically valuable. NASA just has to pick one."

In the early days of the space program, O'Rourke said, "Venus and Mars shared the glory. The first successful interplanetary flyby mission went to Venus.... The Soviet Union sent landers to Venus. But in recent decades, Venus has absolutely been neglected and Mars stole the show."

Destination: Mars

We have a clearer picture of Mars's magnetic properties because it has been the subject of so many recent missions.

According to Jennifer Buz, a postdoctoral scholar in the Department of Astronomy and Planetary Science at Northern Arizona University, travelers to Mars may want to avoid the northern hemisphere if they are going to rely on a compass. "Most of the north is unmagnetized, [so] it wouldn't do much," she said. "But as you go south, there is a region where the crust is really strongly magnetized, in alternating fashion. Some people think it's like the magnetic seafloor stripes that we have on Earth. If you were to traverse significant lengths of the southern hemisphere [on Mars], the compass would completely switch direction multiple times."

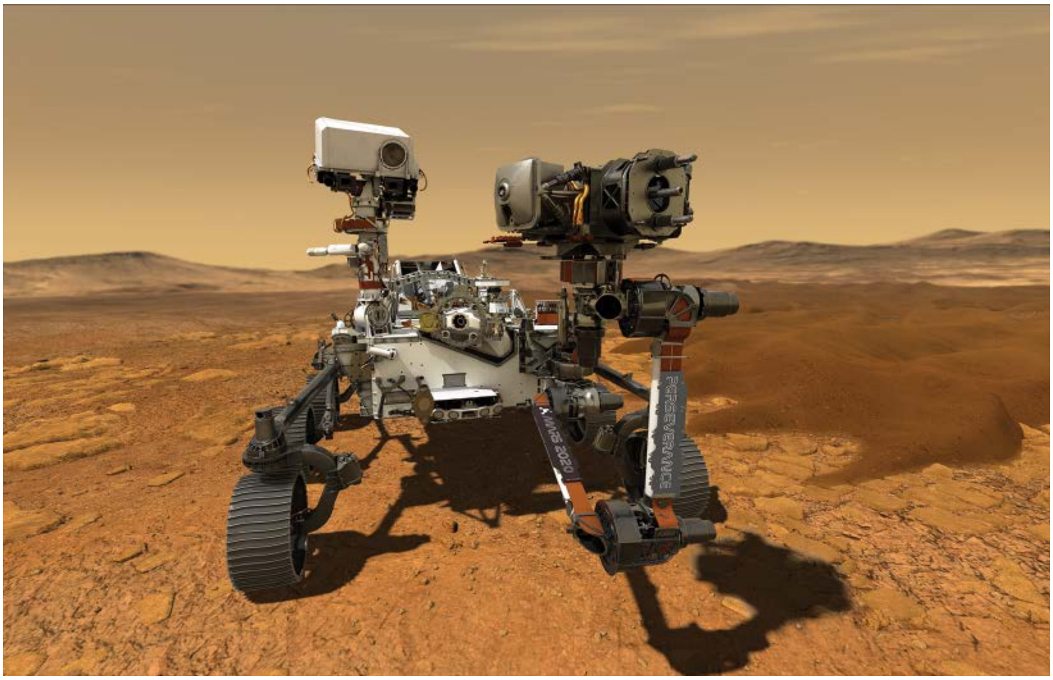
These anomalies indicate that Mars once had a core dynamo and suggest that its magnetic field was strong for its size, about as strong as Earth's. "But there are ways to explain that," said Buz. "Mars has a lot more iron, so it could have a more significant core. And then because Mars is smaller, the field at the surface is closer to the core."

It would be possible to study the core by observing seismic waves traversing the planet from several locations simultaneously. But there is only one working seismometer on the planet, brought there on the 2018 Mars InSight Mission.

The InSight lander also had a magnetometer on board. "And from that single data point, where that probe landed, we were able to validate a lot of the global mapping from orbit," Buz said. "When it landed, [we found that] the field was a lot stronger than we had modeled."

But here, too, data from one instrument at one location are limiting. "It would be really great if we could have a magnetometer on one of the rovers," said Buz. "To see the minute changes in the magnetization as the magnetometer traverses the planet would shed a lot of light on why [Mars has] such variable crustal magnetization."

NASA's next Mars mission will arrive in February with a rover, Perseverance, but without a magnetometer. But it looks like Buz's wish will be fulfilled by a Chinese mission that launched in the same month, July 2020. Tianwen-1 (the name means "Heavenly Questions") will also arrive in February, and put a rover down in May. This rover carries the Mars Surface Magnetic Field Detector, which will measure the field to an accuracy of better than 0.01 nanotesla. That's less than a millionth of the field strength of Earth. "Historically, it's been hard to access data from Chinese missions," Buz said, "but it looks like this mission has a lot of international collaboration. I'm excited for their results."



The next Mars mission will arrive in February with a rover, Perseverance, but without a magnetometer. Credit: NASA/JPL-Caltech

Destination: Gas Giants

If you're the kind of traveler who is slightly annoyed that your magnetic compass doesn't quite point to the geographic North Pole on Earth, then Saturn is your magnetic Shangri-la, while you may give Jupiter a pass.

"Saturn's field is unique: It's almost perfectly axisymmetric," said Stanley. But on the other gas giant of the solar system, the compass is tricked by flux patches not far from the poles, where additional field lines emerge.

The flows of conducting material that a dynamo needs are not located in the metal cores of gas giants—if the planets even have them.

Instead, scientists think the flows arise at higher levels, where the hydrogen that makes up the bulk of these planets is hot and pressurized enough to become metallic.

Modelers can produce a field like Jupiter's, but as for Saturn, "it's really hard to generate a dynamo that produces a symmetric field," said Stanley. "You have to do something special in the interior."

This would perhaps be some kind of shielding layer around the dynamo. "As you go deeper into Saturn and the hydrogen becomes metallic…the helium that is mixed in with the hydrogen doesn't transition [to metal], and it can actually rain out of the hydrogen." The result is a helium-depleted layer covering the dynamo region. "It could act as a shield that gets rid of any of the nonaxisymmetric fields that we otherwise might see at the surface."

Destination: Galilean Moons

While you're in the neighborhood of the gas giants, it seems a shame not to have a quick visit to some of the Galilean satellites. "They're really interesting," said O'Rourke.

Of Jupiter's Galilean moons—Io, Europa, Ganymede, and Callisto—the first three are thought to have iron cores, based on their gravitational pull on the Galileo spacecraft that cruised around the Jovian system from 1995 to 2003. Only one of them, though, Ganymede, has a core with an active dynamo, producing a strong dipole field.

Why the others don't is a puzzle O'Rourke is working on. "It could be related to the amount of tidal heating in these worlds. Io, of course, is super close to Jupiter—it is being violently heated by tides, and if the rocky part of Io is superhot, maybe even liquid, that would insulate the metal core. Whether or not that process also works on Europa is totally unclear."

Not having a dynamo doesn't mean a Galilean moon can't be an interesting place to bring a compass. Near Europa and Callisto, for example, Galileo measured perturbations of the magnetic field of Jupiter. Instead of dynamos, these moons are thought to be the solar system's induction coils. Stimulated by changes they experience in the magnetic field of Jupiter as it rotates, electric currents flow inside the moons, and these in turn bring about magnetic fields that counteract the changes. The existence of the fields is taken as evidence that hidden under the surfaces of Europa and Callisto are salty oceans. Compass readings on these moons will be hard to interpret without detailed knowledge of where the satellite is in its orbit.

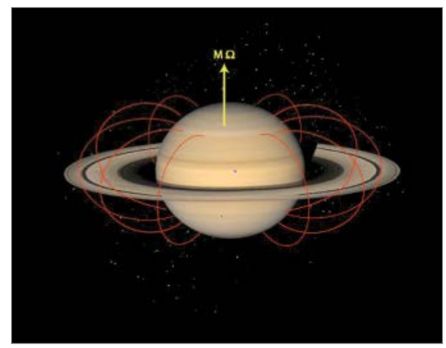
INSTEAD OF DYNAMOS, THESE MOONS ARE THOUGHT TO BE THE SOLAR SYSTEM'S INDUCTION COILS.

Destination: Ice Giants

Great caution is advised when magnetically navigating Uranus and Neptune. The magnetic fields of the solar system's two ice giants are not dipolar but multipolar, said Stanley. "They have lots of places where field lines come out of the planet and go into the planet. So you never know where your compass is going to be pointing."

The poles of our solar system's ice giants may not even be fixed. "The only data we have [are] from a single flyby of both planets by the Voyager II spacecraft in the late '80s," said Stanley. "So all we have is a snapshot in time of the field. We think they move around. But we don't know at what speed."

Uranus and Neptune consist of water, ammonia, and methane ices, which may contribute to the planets' magnetic potential. "When you're thinking about dynamos and magnetic field generation," said Stanley, "you have to ask: Where in the planet can I get a material that is going to be fluid, and a good electrical conductor? For Uranus and Neptune, as you descend into the planet, water—as you keep putting it under higher and higher pressure—becomes ionic. The bonds in the molecules break, and you have OH^{-s} and H^{+s} ions of water. And those can carry electric charges, creating a current. So we think the dynamos in Uranus and Neptune happen in the ionic water layers. We don't know how deep the dynamo region goes, and we really don't understand what happens to the water."



Saturn's magnetic field lines (red) are symmetric, and the planet's dipole axis (M) and its rotation axis (Ω) are nearly perfectly aligned. Credit: NASA/JPL-CaltechDQ: Your compass may actually measure fields in the magnetosphere of Mercury that are caused by interaction with the solar wind.

Some Final Pointers

Clearly, tourist excursions in the solar system are not for the fainthearted—and at present, travel insurance is available only for the rocky planets, with deductibles varying from very reasonable (the Moon) to quite steep (Venus). This may well change as further data become available and magnetohydrodynamic models improve. Those who have an itch to go farther afield should follow the Earth science journals for the latest developments and, of course, Eos, *proudly your companion in all your interplanetary adventures.*

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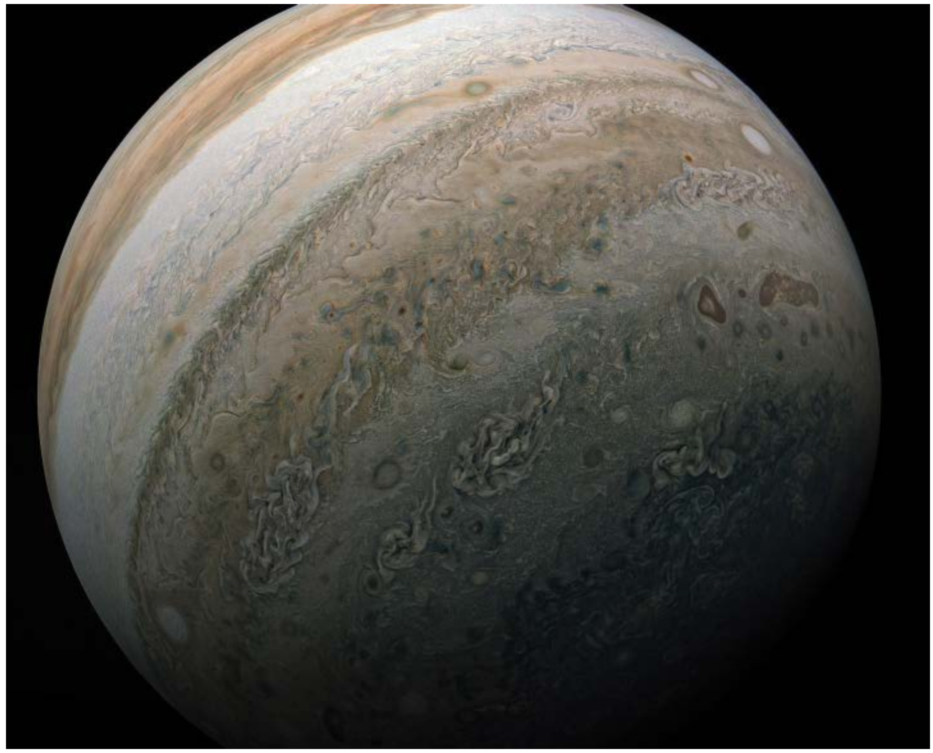
A Juno Era Model of the Jovian Magnetosphere

Jupiter creates the solar system's most powerful planetary magnetic field, and understanding its region of influence, called the magnetosphere, is vital to nearly all observations of the Jovian system. The first estimates of Jupiter's magnetosphere were developed in anticipation of the first spacecraft flybys in the 1970s. The 1979 visits by the dual Voyager spacecraft provided data sufficient to construct a robust empirical model of the magnetosphere within 30 Jovian radii (R_J) of the planet.

The Voyager model, which represents Jupiter's magnetospheric configuration with a disklike geometry, remains in use today. However, the arrival of NASA's Juno spacecraft in 2016, which provided highly detailed measurements of Jupiter's plasma environment, revealed discrepancies in that model. *Connerney et al.* extend the Voyager model and refit it to Juno observations to improve mission planning and data interpretation. The result is a model that empirically describes the magnetosphere without attempting to explain the physical processes that produce it.

The authors fit the Voyager model with all high-resolution Juno magnetic field data collected within 30 R_J on Juno's first 24 polar orbits. That model relies on an axisymmetric current sheet that encircles Jupiter, with azimuthal currents confined to a washer-shaped region near the magnetic equator. The researchers augmented this system of azimuthal currents with another system of radial currents that flow outward from the inner edge of the disk. The resulting best fit model describes the magnetosphere as a slightly inclined disk with a total thickness of 7.2 R_J, an inner radius of 7.8 R_J, and an outer radius of 51.4 R_J.

This Juno-based model was evaluated through observations of charged particle interactions with Jupiter's large moons and was found to substantially outperform the Voyager era one. The authors also examined orbit-to-orbit variations in the modeled current sheets; the azimuthal current appears to remain steady, whereas the radial current shows larger change. This variation may indicate activity in the magnetosphere, the researchers noted, and may be useful in interpreting Jupiter's aurorae. (*Journal of Geophysical Research: Space Physics*, https://doi.org/10.1029/2020JA028138, 2020) —**Morgan Rehnberg**, *Science Writer*



This view of Jupiter was captured by the Juno spacecraft on 17 February 2020.Credit: Image data: NASA/JPL-Caltech/SwRI/MSSS; image processing: Kevin M. Gill

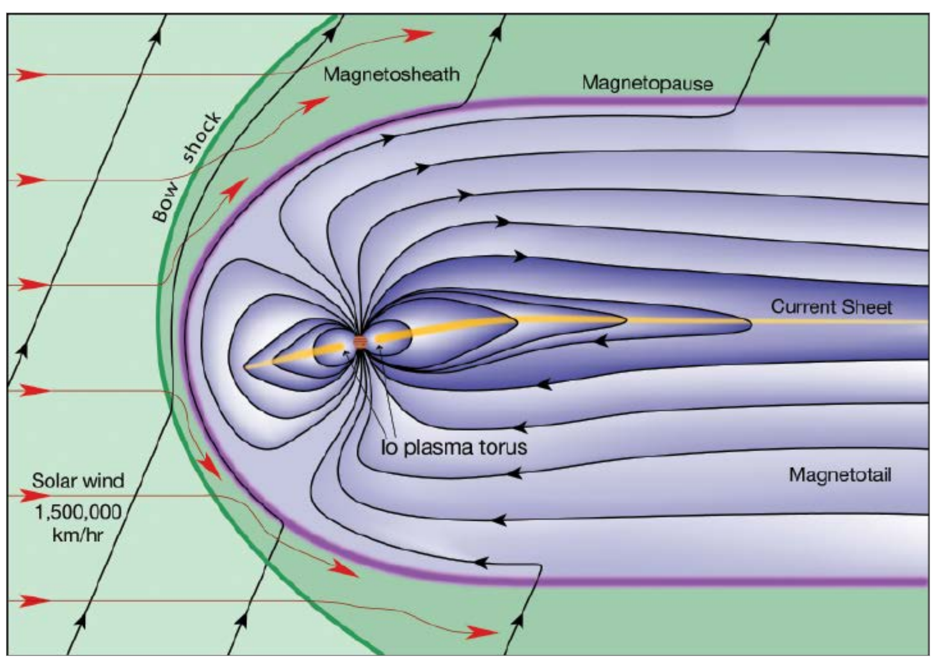


Illustration of Jupiter's complex magnetosphere, including the current sheet. Credit: Fran Bagenal and Steve Bartlett

How Long Does Iron Linger in the Ocean's Upper Layers?

Iron is in our blood, our buildings, and our biomes. In our oceans, iron helps regulate global climate by sustaining carbon-catching phytoplankton. However, current environmental models have difficulty pinning down the relationship between climate and marine iron cycling because they have few data to go on.

In new research, *Black et al.* conducted an extensive observational study as part of the international GEOTRACES program to investigate iron residence times in the top 250 meters of the ocean and to close gaps in previous results.

Iron in the ocean comes in various forms, depending on its bonding with other materials. Particulate iron may coat dust grains suspended in the water column, for example, and is largely inaccessible to marine life because it typically sinks out of the upper ocean before it dissolves and becomes available for organisms. Dissolved molecular iron, meanwhile, is more bioaccessible. Because these and other forms of iron behave differently in marine environments, their residence times will differ.

Subantarctic waters along the West Antarctic Peninsula are seen from the R/V Palmer *in 2009. Credit: Ken Buesseler*

Whereas previous studies have estimated residence times ranging from days to years, the new research narrows the window, finding that in most cases, the residence time for total iron is between 10 and 100 days. Subantarctic regions are an exception. As there is very little iron in these areas, residence times depend on local events like infusions of iron from atmospheric dust or from eddies and vary from just a day up to decades.

The researchers also found that dissolved iron has inconsistent residence times that vary in monthlong to yearlong cycles depending on local conditions. Organisms may respond to seasonal or other changes in their environment to take up more or less dissolved iron.

All told, the residence times of iron indicated in the new study are shorter than previous studies have estimated. The researchers suggest that the new data and results should help to develop improved biogeochemical models that better predict carbon sequestration in the ocean. (*Global Biogeochemical Cycles*, https://doi.org/10.1029/2020GB006592, 2020) **—Elizabeth Thompson,** *Science Writer*

Capturing Heat-Driven Atmospheric Tides on Mars

On Mars, heat from the Sun drives daily changes in temperature, wind, and pressure in the atmosphere. Known as atmospheric tides, these regular patterns play a major role in shaping the planet's weather.

Atmospheric tides exist on Earth as well, but they have a much greater influence in Mars's thin atmosphere. The details and drivers of atmospheric tides on Mars have remained unclear, however. Now *Forbes et al.* present new spacecraft data and model simulations that deepen our understanding of tidal patterns in the middle and upper atmosphere of Mars.

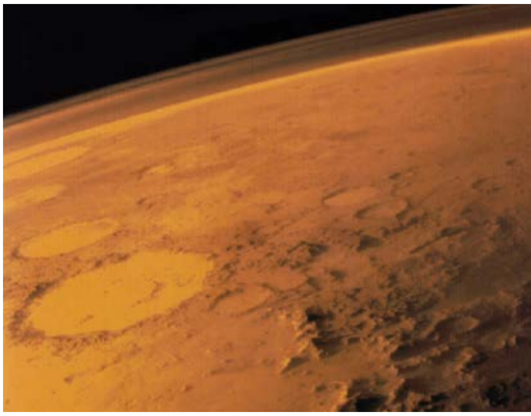
The new observations came from NASA's Mars Climate Sounder (MCS), an instrument mounted on the Mars Reconnaissance Orbiter, which has circled the Red Planet since 2006. The researchers analyzed about 9 years of MCS-captured temperature data for the middle atmosphere, revealing how tidal patterns shift as the north-south angle at which Mars faces the Sun changes over the course of each year.

Key patterns emerged from the MCS data, including eastward and westward propagating tidal pulses that repeat daily or twice daily. Some of these tidal patterns match the path of sunlight as it sweeps across the planet, others are out of sync with the Sun but still follow a regular schedule.

The MCS observations aligned well with predictions of tidal patterns from the Laboratoire de Météorologie Dynamique's Global Climate Model, as captured in the Mars Climate Database. The model predictions also showed how these middle-atmosphere tidal patterns could give rise to longitudinal variations in density that have been observed in the upper atmosphere by the Mars Global Surveyor.

In addition, the researchers used the model predictions to explore how certain atmospheric processes could drive tidal patterns that result in variations in atmospheric density at different altitudes and latitudes, and at different times of the year.

The findings support the use of the Mars Climate Database to study atmospheric tides and could boost scientists' ability to predict the planet's weather. The researchers say they plan next to compare model predictions with observations from additional spacecraft and that future work may examine discrepancies between predictions and observations. (*Journal of Geophysical Research: Space Physics*, https://doi.org/10.1029/2020JA028140, 2020) **—Sarah Stanley,** *Science Writer*

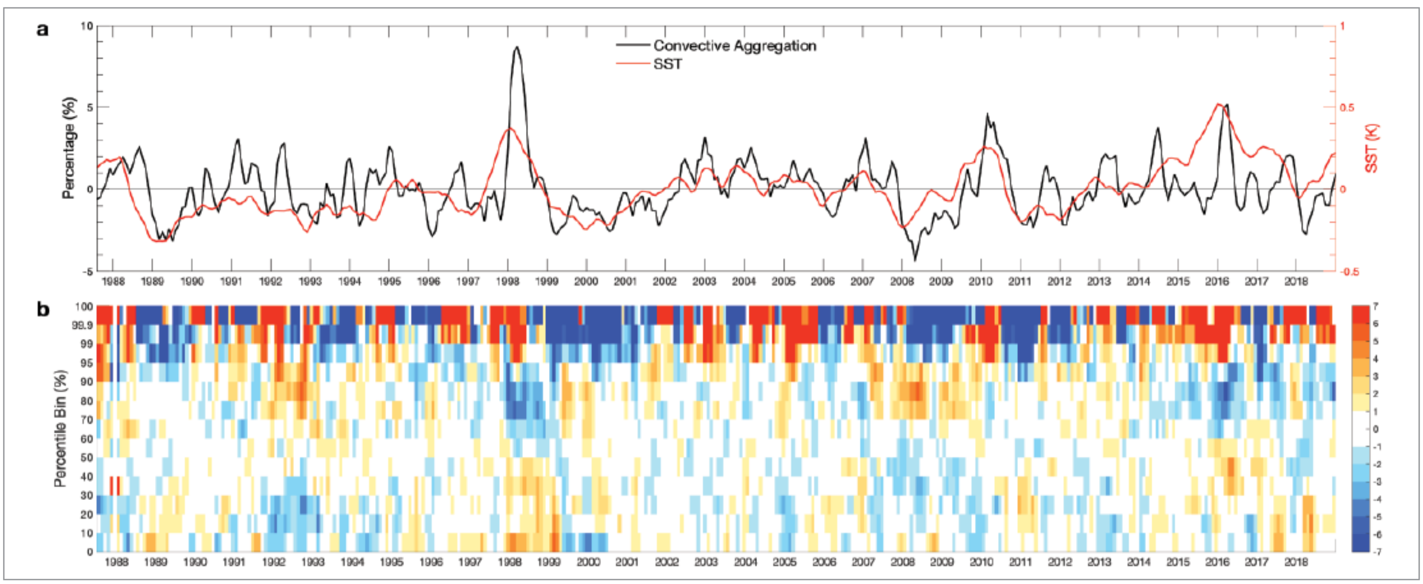


The thin atmosphere of Mars, visible on the horizon in this image taken by the Viking 1 spacecraft, undergoes daily variations in temperature, wind, and pressure driven by solar heating. Credit: NASA

Ensemble Modeling of Coronal Mass Ejection Arrival at 1 Astronomical Unit

The Solar Stormwatch project coordinates citizen scientists in tracking coronal mass ejection (CME) events observed in white light from the Solar Terrestrial Relations Observatory (STEREO) A and B spacecraft at different heliographic longitudes orbiting at 1 astronomical unit. The HI1 instruments, identical on both spacecraft, are white-light imagers that observe sunlight that has been Thomson scattered by solar wind electrons. *Barnard et al.* use the HUXt numerical model, which uses these STEREO white-light images as input, treats the solar wind as a 1D incompressible fluid and solves for arrival time of the CME perturbation of the solar wind at Earth. Ensemble modeling of different determinations of the inner boundary condition improves the forecast arrival time of CME disturbances of the solar wind at Earth, an important driver of space weather. Radiation threats to spacecraft and astronauts, as well as ground-induced currents that can shut down power grids, are examples of space weather effects produced by strong CMEs. Advanced warning of arrival time may allow mitigation. (https://doi.org/10.1029/2020AV000214, 2020) **—Mary Hudson**

More Clustered Clouds Amplify Tropical Rainfall Extremes



(a) Observed time series of sea surface temperature (SST) anomalies (red; in Kelvins) and percentage anomalies of degree of convective aggregation (black; in %) in the tropics between 30°S and 30°N. (b) Monthly percentage anomalies of instantaneous precipitation frequency in 13 bins. Higher frequency of extreme precipitation corresponds to warmer SST anomalies and the higher degree of large-scale aggregation. Credit: Dai and Soden, 2020

Precipitation extremes, already shown to be increasing, have substantial implications for both human and natural systems. Extreme precipitation is expected to increase further with warming from a simple thermodynamic relation that implies an exponential increase in atmospheric moisture with temperature.

However, within the tropics, the rate of intensification of extreme precipitation with warming is implied by the thermodynamic argument, hinting at an unknown contribution from atmospheric dynamics. *Dai and Soden* reveal that the degree of cloud clustering (i.e., convective aggregation) amplifies the response of tropical precipitation extremes to surface warming on a year-to-year basis in both satellite observations and climate model simulations. More specifically, precipitation extremes and convective aggregation increase during El Niño events compared with La Niña events. The newly revealed linkage between convective aggregation and precipitation extremes offers insights into their potential response to future warming. (https://doi.org/10.1029/2020AV000201, 2020) **—Sarah Kang**

Atmospheric Sciences

COLORADO STATE UNIVERSITY ATMOSPHERIC SCIENCE TENURE TRACK FACULTY POSITION AND DIRECTOR OF THE COOPERATIVE INSTITUTE FOR RESEARCH IN THE ATMOSPHERE

Colorado State University invites applications for a tenure track faculty position in the Department of Atmospheric Science. This hire will also serve as Director of the Cooperative Institute for Research in the Atmosphere (CIRA). The faculty appointment will be made at the rank of Associate Professor or Professor. We solicit candidates in CIRA's core focus area of merging satellite observations and models. This is interpreted as expertise in Satellite Remote Sensing, Regional and Global Model Development, or Data Assimilation, with emphasis on individuals working at the interfaces of these areas.

Applications and nominations will be considered until the positions are filled; however, applications should be received by January 20, 2021 to ensure full consideration. The search will remain open until the position is filled. Application materials of candidates, including letters of recommendation, will only be made available for review by the broader faculty of the Department of Atmospheric Science if the applicant reaches the semifinalist stage. Full details of the position can be found at the link below. Applicants should submit a cover letter, one to two page statements on their vision for CIRA leadership (uploaded to the special required documentation slot) and on research and teaching interests, a statement on your commitment to diversity and inclusion (uploaded to the other slot), a curriculum vitae, and the names of four references (who will not be contacted without prior notification of the candidate) at the following link: http://jobs.colostate.edu/postings/81206. Applications must be submitted online.

Please address inquiries about the position to:

Professor Peter Jan van Leeuwen, Search Committee Chair
Department of Atmospheric Science
Colorado State University
Fort Collins, CO
80523-1371
Peter.vanLeeuwen@colostate.edu

In collaboration with NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), the Atmospheric and Oceanic Sciences Program at Princeton University solicits applications to its Postdoctoral Research Scientist Program funded by the Cooperative Institute for Modeling the Earth System (CIMES).

The AOS Program and GFDL offer a stimulating and supportive environment with significant computational and intellectual resources in which to conduct collaborative or independent research for the modeling, understanding and predictability of the Earth System from weather to centennial time scales. We primarily seek applications from recent Ph.D.s for postdoctoral positions but will accept applications from more experienced researchers. Appointments are made at the rank of Postdoctoral Research Associate, or more senior, initially for one year with the possibility of renewal for a second year based on satisfactory performance and continued funding. A competitive salary is offered commensurate with experience and qualifications.

We seek applications in all areas of earth system science within the three research themes of CIMES: 1) Earth System Modeling; 2) Seamless prediction across time and space scales; 3) Earth System Science: Analysis and Applications. The broad scope is improved representation of processes in models, high-resolution modeling, and advancing the understanding of the Earth System including its variations, changes, feedbacks, and sensitivity utilizing models and observations. Current areas of particular interest are: Stratosphere-troposphere radiative-chemical-dynamical interactions, and predictability; Aerosol-cloud-precipitation-radiation interactions including ice and mixed-phase microphysics, and effects on weather and climate; Lower atmosphere-surface interactions over land and ocean; Land surface processes and atmospheric precursors of risks; Ocean dynamics and its role in climate, and impacts on coastal regions and marine resources; Subseasonal to seasonal predictions of high-impact weather events; Decadal projections of regional climate and extremes using large high-resolution climate model ensembles; Detection and causal attribution of climate change; Applications of novel machine learning methods; Downscaling techniques to address regional climate and weather impacts.

Further information about the AOS Program may be obtained from: http://aos.princeton.edu, and about GFDL from http://www.gfdl.noaa.gov. Applicants are strongly encouraged to contact potential hosts at GFDL and/or Princeton University prior to application to discuss areas of possible research.

Complete applications, including a CV, copies of recent publications, three letters of recommendation, and a research proposal of approximately 5 pages including the project title, should be submitted by December 8th, 2020 for full consideration. A goal of our department is diversifying the community of scientists and making the field more equitable and inclusive. With this in mind, we will take into consideration personal experiences as well as efforts in education, outreach or other service activities related to Earth system science or other sciences, which may be described in a separate section of the research statement. Applicants must apply online to https://www.princeton.edu/acad-positions/position/18341. We would like to broaden participation in earth system scientific research and therefore encourage applications from groups historically under-represented in science. These positions are subject to the University's background check policy.

Princeton University is an equal opportunity employer and all qualified applicants will receive consideration for employment without regard to age, race, color, religion, sex, sexual orientation, gender identity or expression, national origin, disability status, protected veteran status, or any other characteristic protected by law.

The laboratory of Professor Ching-Yao Lai in the program of Atmospheric and Oceanic Sciences (AOS) and Geoscience (GEO) at Princeton University invites applications in the broad areas of fluid dynamics and geophysics for a postdoctoral position starting March 2021 or later. A Ph.D. in physical sciences, engineering, applied mathematics, or a related field is required prior to starting. We are looking for candidates with a keen interest in fluid dynamics, nonlinear dynamics, interfacial phenomena, ice dynamics, climate science, or fluid-structure interactions. Research experience in mathematical modeling, numerical methods or machine learning is preferred. Our group aims to combine mathematical models (analytical or computational) and machine-learning algorithms to address the environmental and climate challenges facing society, such as predicting the future of ice dynamics in a warming climate and improving its physical representation in climate models. Appointments are for one year, renewable annually based on satisfactory performance and available funding. See our group website for more info about our research: cylai.princeton.edu

The Princeton AOS program emphasizes theoretical studies and numerical model studies of the global climate system, and applicants are expected to have a strong background in natural sciences and mathematics. The AOS program benefits from the research capabilities of the Geophysical Fluid Dynamics Laboratory (GFDL) of the National Oceanic and Atmospheric Administration. Many GFDL climate modelers are active in the AOS program as lecturers and broadly collaborate with AOS students and postdocs.

Applicants must apply online https://www.princeton.edu/acad-positions/position/18221 by February 1, 2021, 11:59 EST. Submit a cover letter, CV, one or more first-author publications, contact information for at least three references, and a 1-2 page research statement including previous research accomplishments and current interests.

This position is subject to Princeton University's background check policy.

Princeton University is an equal opportunity/affirmative action employer and all qualified applicants will receive consideration for employment without regard to age, race, color, religion, sex, sexual orientation, gender identity or expression, national origin, disability status, protected veteran status, or any other characteristic protected by law.

The Atmospheric and Oceanic Sciences Program at Princeton University, in association with NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), seeks to fill up to three postdoctoral or more senior research positions in a research initiative aiming at advancing the fundamental understanding of the roles of clouds and radiation in affecting Earth's climate and weather, and evaluating/improving their representation in GFDL climate/weather models. The recently developed GFDL climate models (CM4 and ESM4) are among the best-performing CMIP6 models in terms of mean climate and variability. They use the same FV3 dynamical core as the current NOAA/NWS weather forecast model. CM4 also forms the basis of a prediction model (SPEAR) and can be configured into a limited-domain cloud-resolving model (CRM) for process-level studies. GFDL has a long tradition in conducting cutting-edge research related to clouds/aerosols, radiation, circulation, precipitation and extreme weather/climate events. This search represents a concerted effort to push this prominent research direction to new levels.

The first position will be in the area of aerosol-cloud interactions and indirect effects, with focus on understanding the controlling factors of the magnitude and spatiotemporal distribution of model-simulated aerosol indirect effects, using satellite/in-situ observations to validate the model representation of aerosol/cloud processes, and developing/implementing parameterizations of ice nucleation and mixed-phase cloud microphysics.

The second position will be in the area of cloud feedbacks, with focus on understanding the key processes in affecting the cloud feedbacks and climate sensitivity in coupled ocean-atmospheric models. This includes an investigation of effects of SST warming patterns on cloud feedback strength and coupled model simulation of historical and future warming trends.

The third position will be in the area of atmospheric radiative transfer and cloud radiative effects, with primary focus on designing a new line-by-line atmospheric radiative transfer code that will serve as a benchmark standard for weather/climate models. The position will also involve improving the model representation of cloud microphysics-radiation interactions based upon results from the aforementioned radiation code.

The ideal candidates have to demonstrate a strong background in atmospheric and climate modeling, and climate science, as well as experience in using, developing, and analyzing numerical models and/or large observational datasets.

Candidates must have a Ph.D. in atmospheric physics, dynamic meteorology, Earth system science, climate studies, or related fields. The initial appointment is for one year with the possibility of renewal subject to satisfactory performance and available funding.

Complete applications, including a cover letter, CV, publication list, a statement of research interests, and contact information of 3 references should be submitted by December 1, 2020 for full consideration. Applicants should apply online to https://www.princeton.edu/acad-positions/

The Department of Earth and Space Sciences(ESS) at Southern University of Science and Technology of China (SUSTech) invites applications for **tenure-track (or tenured) faculty positions at the ranks of Assistant, Associate, and Full Professors.** Applicants must have earned a doctoral degree in Geophysics Structure Geology Geodesy Space Physics Planetary Science or closely related fields. Successful applicants will be expected to establish a robust, externally funded research program and demonstrate strong commitment to undergraduate and graduate teaching, student mentoring, and professional services. These positions will remain open until filled. For more other information about ESS, please go to the website **https://ess.sustech.edu.cn/**.

SUSTech is a public university founded in Shenzhen, China. It is intended to be a top-tier international university that excels in interdisciplinary research, nurturing innovative talents and delivering new knowledge to the world.SUSTech was born in 2011 with a mission to reform higher education in China. Since then, it has been widely regarded as a pioneer and innovator in collectively moving China's higher education forward to match China's ever-growing role in the international arena. Research, Innovation and Entrepreneurship are the three pillars for SUSTech to stand out with distinctive Characteristics.

To apply, please submit an e-mail application that includes a cover letter, a CV with a full list of publications, a research statement, a teaching statement and contact information for three references to Prof. Xiaofei Chen at **chenxf@sustech.edu.cn.**

position/16001. For more information about the research project and application process, please contact V. Ramaswamy (V. Ramaswamy@noaa.gov) for general inquiries, Yi Ming (Yi.Ming@noaa.gov) for the first position, Ming Zhao (Ming.Zhao@naoa.gov) for the second position, and David Paynter (David.Paynter@noaa.gov) for the third position.

This position is subject to Princeton University's background check policy.

Princeton University is an equal opportunity/affirmative action employer and all qualified applicants will receive consideration for employment without regard to age, race, color, religion, sex, sexual orientation, gender identity or expression, national origin, disability status, protected veteran status, or any other characteristic protected by law.

Interdisciplinary

The University of Georgia's (UGA) Center for Applied Isotope Studies (CAIS) is seeking a Director at the rank of Assistant, Associate, or Senior Research Scientist. The CAIS is the largest isotope geochemistry/radiocarbon AMS dating facility in the U.S. and is accredited under ISO/IEC 17025:2017. CAIS contains state-of-the-art facilities for radiocarbon dating, environmental analyses, food flavor and beverage authenticity testing, and bio-based product testing (https://cais.uga.edu). CAIS's 40+ scientists collaborate in research and method development, serve the UGA research community and work with worldwide academic institutions, government agencies, and private companies. The Director will oversee scientific, fiscal and regulatory activities, and work closely to develop, refine, and implement a vision for the Center's continuing growth and preservation of ISO/IEC accreditation. The Director interfaces with the UGA Office of Research for policy, reports, and personnel administration. The Director will have a commitment to a diverse workforce and maintain a high quality of researchers and staff members who are committed to world-class science and technology. The Director provides primary leadership for a robust and technologically advanced research and service center that generates annual revenues of approximately \$3M. The Director also ensures that CAIS operates with fiscal and scientific integrity and will be responsible for ensuring that it supports interdisciplinary work at UGA and offers training opportunities for undergraduate and graduate students. CAIS collaborates with UGA's Departments of Chemistry, Geography, Geology, Marine Science, Ecology, and Archaeology. For more information go to:

https://www.ugajobsearch.com/postings/175843

Tenure Track Faculty Position in Climate and Space Sciences and Engineering, University of Michigan

The Department of Climate and Space Sciences and Engineering (CLaSP) in the College of Engineering at the University of Michigan in Ann Arbor invites applications for a tenure track faculty position with expertise in one of the following areas.

1) Essential components of the stressed climate system–someone who can bridge and strengthen our existing research portfolio. Specific subdisciplines of interest include meteorology and climate dynamics, polar science, atmospheric chemistry and air quality, clouds and water cycle feedbacks, and impacts of climate mitigation. The department welcomes expertise in either experimental (satellite, airborne, or ground-based instrumentation) or modeling (numerical weather prediction, climate modeling, machine learning, big data applications) areas.

2) Space science – someone with strong interest and expertise in plasma processes preferably of the near-Earth space environment. We seek candidates interested in advanced numerical methodologies and models and/or in the development, operation, and analysis of data from related spaceborne space science instruments. We welcome applications from candidates whose research addresses cross-disciplinary areas that complement our existing strengths in space sciences and engineering and the development of space instrumentation and missions.

Although the position is open to all ranks, we especially seek candidates at the Assistant Professor level. We look for candidates who are capable of developing an internationally recognized research program, successfully competing for external funding, mentoring doctoral students, and participating in our educational programs at the graduate and undergraduate levels.

Applications should include a cover letter, CV, research and teaching statements, a statement describing any activities, contributions, or plans related to supporting diversity, equity, and inclusion, and a list of four references with contact details. For full consideration, applications compiled into a single PDF should be received before December 15th, 2020. Applications should be addressed to clasp-fac-search@umich.edu. Questions about the position or application process can be directed to the search committee chair Chris Ruf (cruf@umich.edu). The availability of this position is contingent upon final University approval.

The University of Michigan is committed to diversity, equity and inclusion. CLaSP and the College of Engineering are especially interested in exceptionally well qualified candidates who will contribute, through their research, teaching, and service, to the department's goal of eliminating systemic racism and sexism by embracing our culture of Diversity, Equity and Inclusion (DEI). Women, minorities, individuals with disabilities, and veterans are encouraged to apply. The University is also responsive to the needs of dual-career couples. The University is a non-discriminatory, affirmative action Employer. The Michigan Engineering component of the University's comprehensive, five-year, DEI strategic plan can be found at: http://www.engin.umich.edu/college/about/diversity.

Michigan Engineering's vision is to be the world's preeminent college of engineering serving the common good. This global outlook, leadership focus, and service commitment permeate our culture. Our vision is supported by a mission and values that, together, provide the framework for all that we do. Information about our vision, mission and values can be found at: http://strategicvision.engin.umich.edu/.

The University of Texas Arlington (UTA) is spearheading a new, multidisciplinary hiring initiative in support of our strategic plan, Bold Solutions | Global Impact.

UTA is uniquely positioned to address the epic challenges that face our growing urban regions. By leveraging our expertise in the critical areas outlined in the strategic plan, the University is poised to help emerging megacities like the Dallas-Fort Worth Metroplex become sustainable economic and cultural centers that raise the prospects for prosperity and enhance quality of life.

One of UTA's goals is to increase the representation of historically underrepresented faculty, including underrepresented minority faculty in general and women faculty in STEM fields. Increasing the representation of faculty members who understand, and have overcome, race, gender-based, and ability barriers and biases is vital to the success and well-being of our students. Diversity is critical to academic excellence. As research demonstrates, diverse teams are more innovative, productive, and solve complex problems faster. UTA is committed to preparing all students to live and work in an increasingly global, diverse, and interconnected world by exposing them to a wide array of ideas, experiences, cultures, and individuals.

We are looking for strong tenure track faculty who will contribute in their geoscience or environmental science area to the unprecedented excellence in research, teaching, and community engagement taking place in the College of Science.

Applicants should have a doctoral degree in geoscience or environmental science. Candidates in their early career must demonstrate strong potential to develop a research program supported by external funding, while more established candidates must demonstrate active, externally funded research agendas.

Application Procedure

Review of applications will begin immediately and continue until the position is filled. Applicants must apply online at https://uta.peopleadmin.com/postings/13077.

A complete application includes: 1) curriculum vitae, 2) summary of current and proposed research (max. two pages), 3) statement of teaching interests (max. one page), and 4) names and email addresses of three references.

Question regarding this position may be directed via email to Dr. Majie Fan, College of Science Search Committee (Email: mfan@uta.edu) or the administration of the Department of Earth and Environmental Sciences (Courtony Hill, Email: courtony.hill@uta.edu).

Hello from 14,115 feet!

My name is Lauren Haygood and I'm in the accelerated master's geoscience program at the University of Tulsa. In summer 2019, I attended Oklahoma State University's field camp in Cañon City, Colo.

I and 60 other students were tasked with mapping different areas, making stratigraphic columns, and completing a weeklong geophysics project. This photo is from one of our field trips to Pikes Peak, which essentially comprises a batholith composed of Pikes Peak granite.

We made lots of great memories. Wish you all could've been here!

—**Lauren Haygood,** University of Tulsa, Okla.

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